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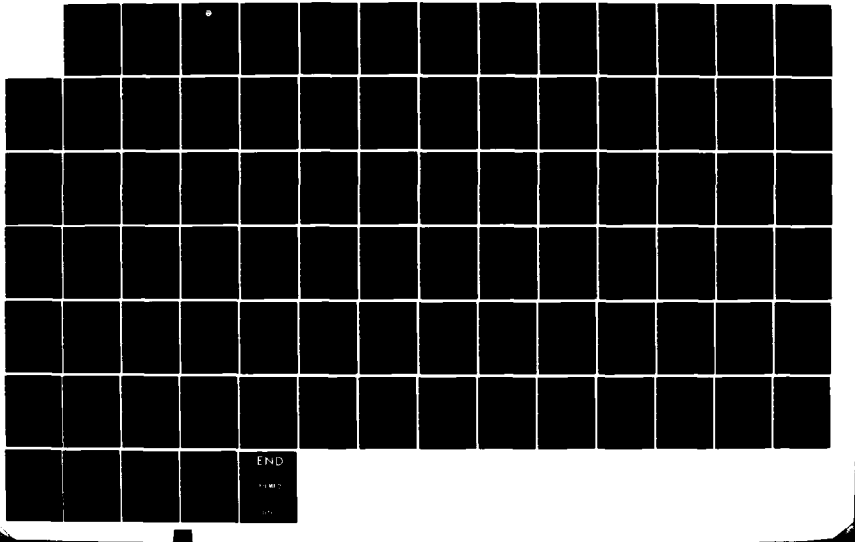

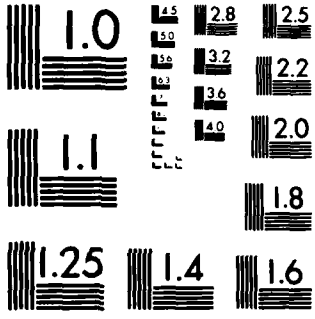

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ARTIFICIAL INTELLIGENCE AND BIONICS WORKSHOP REPORT

J. E. Haun
P. E. Nachtigall

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ADMINISTRATIVE INFORMATION

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A summary of the results of the Artificial Intelligence and Bionics Workshop, hosted by the Naval Ocean Systems Center and sponsored by the Office of Naval Research. Workshop was divided into four working groups: sensors, cognitive processing, neurophysiology, and biomechanics. Each working group is represented by a summary and Appendix A contains statements prepared by individual participants.

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EXECUTIVE SUMMARY

INTRODUCTION

This report summarizes the results of the Artificial Intelligence and Bionics Workshop, held in Stowe, Vermont, 11-15 June 1984, hosted by Naval Ocean Systems Center, and sponsored by the Office of Naval Research. The goal of the workshop as stated in the overview that was sent to the participants is summarized as follows:

"This workshop will investigate possible applications of current knowledge of animal sensory, cognitive and motor abilities to discover new directions or issues in the continuing effort to build intelligent systems. It has been organized to foster a productive dialogue between scholars in artificial intelligence and biological intelligence, including such areas as neurophysiology, sensory processes, information capture and transfer, cognitive processing and biomechanical implementation. Our effort will be to explore useful biological models in the further development of artificial intelligence."

DESCRIPTION

In an effort to have the most meaningful interactions possible, the format of the workshop was structured so that there was a minimum of time where all 60 people were together and the majority of time where the people were divided into four working groups. These working groups were chartered to cover the four broad areas of biological interactions with the environment:

- sensors
- cognitive processing
- neurophysiology
- biomechanics

Each of these working groups had individual goals to address that were directed at supporting the overall purpose and goal of the workshop. The following four sections of this report contain the summary description of each of the four working groups and their individual recommendations. In this section of the report we have collated and summarized the recommendations and are presenting those that were voiced in two or more of the working groups, or those that seem to have unique merit relative to a specific group.

The workshop was convened by Dr. Paul Nachtigall the morning of 12 June 1984. After a brief description of the goals of the workshop by Dr. Nachtigall, one of the co-chairmen of each of the four working groups gave a synopsis of what they hoped to address and accomplish during the week. This was followed by the keynote address given by Dr. Marvin Minsky of Massachusetts Institute of Technology. Dr. Minsky's comments stimulated much discussion not only during the question and answer period but during the rest of the week. During the afternoon of the 12th the participants worked in breakout with each of the four working groups on the individual groups' charters. During the afternoon of the second day all of the participants reconvened as a whole group and each of the working groups reported on their progress and problems to date. The entire third day was taken up with working groups in breakout. Friday morning all participants met again as a group where each of the working groups presented their summaries and recommendations.

CONCLUSIONS AND RECOMMENDATIONS

Each of the working groups developed areas it felt represented the most significant directions for near-, mid- and far-term research. These research areas, because of the groups that generated them, were quite diverse, yet similar in that they all revolved around Artificial Intelligence and Bionics. There were however several areas that were mentioned by most if not all of the groups as being "hot" areas of interest that should be pursued.

The first of these "hot areas" is Bionic Sonar. To quote in part from the Sensors Group "... that significant advancements in sonar systems related to Naval use would be realized with a concerted effort in the study of biological sonar signal processing. Both bats and dolphins possess much keener sonar abilities than are presently available in state-of-the-art sonar sets. Combining Artificial Intelligence (AI) techniques from the areas of speech processing and knowledge-based expert systems with information on how biological sonars detect and classify targets is a do-able task in the near term." While this is quite obviously a major area of interest for the Sensors Group, both the Biomechanical and Neurophysiology Groups expressed similar interests. The Biomechanical Group will need the near-term development of a short range, high resolution sonar/radar system to guide the test beds it proposes whereas the Neurophysiology Group calls for research in the areas where biological systems do tasks better than machines such as active and passive sonar.

The next area that was mentioned several times was that the Navy and/or the Department of Defense should institute a major program in Bionics that is intimately tied into programs of Artificial Intelligence. From comments made in open floor discussion, it was obvious that the participants of the workshop felt that (1) the area of bionics has been not given enough attention in the last 10-15 years, yet there have been many advances in the state-of-the-art of the disciplines that would feed the area of bionics and (2) that Artificial Intelligence has much to gain from "Natural" or "Biological" Intelligence that has been basically ignored to date. In addition, the associated comment made by one group to the idea of a major effort such as this was "The matter of funding is important. The amount of the funds is negotiable and needs little discussion here. For so much, we can provide so much, etc. It is the manner of funding that is vitally important. Whatever the amount is, the funding must be nonintermittent over an extended period, say 10 years. There is no sense in embarking on an effort of this difficulty and magnitude with an intermittent or uncertain funding arrangement. That way lies waste, frustration, and failure. Nonintermittent funding, therefore, is a requirement."

The next major area that bears mentioning is the repeated need expressed by all that multidisciplinary group meetings such as this workshop need to continue on a regular basis. The Office of Naval Research was applauded repeatedly for the foresight of putting this meeting together, and at the same time the question, "Why hasn't this been done before?" was asked often. It

seemed obvious to everyone that this should have occurred before and very definitely should continue to occur. Some of the suggestions for the medium for this continued communication are as follows:

- Annual Artificial Intelligence and Bionics Workshops/Conferences
- Inter-lab Visits, Both Short and Long Term
- Joint Research Programs
- Electronic Mail and Database Hook-ups via DARPANET

Another important point made relative to this was the need to include not only established but also young investigators in these areas, including graduate students that will be carrying the research "ball" in the future.

The above recommendations are just the tip of the iceberg. Each of the working groups has many well thought out recommendations for high payoff research in the combined areas of bionics and artificial intelligence, which are outlined in the following sections of this report.

SENSORS WORKING GROUP SUMMARY

INTRODUCTION

The Sensors Working Group of the Artificial Intelligence and Bionics Workshop was composed of fourteen scientists and engineers from the sensory sciences, robotics, signal processing, electroreception, sonar engineering, and animal psychophysics disciplines. Three goals were presented to the participants prior to the first session in order to stimulate and organize an open discussion in each of the topic areas. The goals were (1) to evaluate the current understanding of information encoding and processing by sensory systems, (2) to identify the problems which are impeding research and preventing the development of more complete models of the sensory processes, and (3) to identify and develop lines of research for future sensor applications.

Our intention was to initiate a cooperative exchange of knowledge and theory between the diverse disciplines for the purpose of developing more comprehensive concepts which would coordinate the use of knowledge from these fields. Such coordinating concepts would, we feel, be required for any systematic and efficient development of new sensor applications.

The meeting began with a statement from the co-chairmen describing the general approach and objectives of the group. After the opening statement, the members were asked to introduce themselves and give a general presentation of their background, area of specialization, and most recent research projects. This introductory process was used to facilitate communcations, establish areas of common interest, and generate questions as starting points for subsequent discussions.

The initial discussion concerning our understanding of sensory reception, encoding, and processing mechanisms revealed several problems which seem to interfere with advances in these areas.

Members recognized that, too frequently, model builders confuse the mathematical or logical operations used to explain sensory function with the actual neurological or biological processes which may exist in the animal system. This confusion can divert emphasis away from the fundamental questions concerning the external validity of biological models (i.e., how accurately and completely do they describe the biological processes) and toward problems concerning the internal features of the models themselves or their methods of implementation (e.g., improving computer-hosted algorithms for efficiency or refining mechanical models for specific applications). Though the value of the latter pursuit is well recognized, it does little to reveal the nature of biological processes which, if understood, could yield even more significant benefits.

A second constraint on understanding sensory processes is that sensory systems do not operate in isolation. A molar view must be maintained concerning the interaction of sensory information. Even when concentrating study on a single sensory system, it must be remembered that it is through the dynamic integration of multi-modal sensory inputs that the development of "intelligent behavior" occurs.

It was also recognized that not all the information contained in a sensory stimulus has the same information value and that not all the information may contribute to effective detection or discrimination. Close examination of biological sensors may lead to the development of artificial systems with reduced complexity, without the sacrifice of efficiency, by limiting these systems to the detection and processing of only demonstrably relevant stimulus cues. These comments represent only an abbreviated version of the group's overall topic areas since the group was extremely dynamic and considered a wide range of problems.

Discussion regarding the development of more complete models of sensory mechanisms arose repeatedly throughout the meeting of the Sensors Working Group. Overall, the group expressed a general concern over the limited funding available for basic or non-task-oriented research and the group's general lack of understanding of the funding structures in the defense community. The members were enthusiastic about task-oriented or directly applied research and almost all members expressed a willingness to solve Navy related problems. However, they also thought that task-oriented funding at the expense of basic research acted to delay the formulation and testing of basic underlying processes operating in sensory systems. Additionally, several group members felt there was a need for general development in the area of computational expertise in sensory and signal processing modeling which would in turn lead to the development of testable models. Members believed there were too few experts concentrating on developing working sensory models. In a similar vein, further development was required in the general area of animal psychophysical procedures and conditioning paradigms which are involved in behavioral investigations of sensory systems. Whereas engineering fields have well specified testing and evaluating procedures, and human psychophysical methods have had nearly 100 years of development, the area of animal behavioral control theory and the evaluation of these techniques is still in its formative stages. Substantial effort still needs to be applied to develop new and effective procedures. As the meeting developed, the third and most directly approached goal was introduced: the identification and development of research for future sensor applications.

DIRECTIONS FOR INVESTIGATIONS AND APPLICATIONS

In each of the topics to be described the developing biological model should receive behavioral verification at various stages of development.

1. It is extremely valuable to produce models (mathematical and/or electro-mechanical) of sensory systems as early as possible in conjunction with sensory research. These models are valuable guides to future studies and provide preliminary approximations of systems with limited but useful application.

2. Significant advancements in sonar systems related to Naval use could be realized with the concerted study of biological sonar signal processing. Both bats and dolphins possess keener sonar abilities than are presently available in state-of-the-art sonar sets. Combining artificial intelligence techniques from the areas of speech processing and knowledge-based expert systems with information on how biological sonars detect and classify targets is a do-able task for the near term.

3. In the next several years the greatest use of sensors will be in conjuction with robots and other mobile platforms. Some biological sensory systems appear to be superior to current (man-made) systems and in such cases, efforts should be made to make use of the modeled biological systems. To this end it is important that sensor scientists be involved early in the design process so as to take maximum advantage of the best technology. We have listed two specific biological sensory systems that show potential application in the relative near term (5-10 years):

a. Short range (0-1000 meters) object detection systems based on the elasmobranch (sharks, skates, rays, etc.), passive electromagnetic detection system. Much of the basic information necessary is available but little modeling has been done.

b. There are many needs in the Navy for instruments to locate and identify various substances in the field, e.g., explosives, drugs, and other chemical compounds. Dogs are often used for searches of such compounds. Although considerable information on olfaction (sense of smell) is available, only a few crude models of olfactory systems have been produced. A concerted effort in the area of olfactory modeling could provide useful chemical detectors in a few years.

4. The discovery of new sensory systems, while not impossible, is unlikely. Therefore, in the long term (beyond 10 years) emphasis will most likely be directed toward peripheral, syntactic, and nervous system processing. Toward this end, effort should be increased now in studies of peripheral processing of sensory outputs. With time, the influence of AI will increase.

Other areas of sensor study which show considerable promise for future bionic systems:

1. The fish's auditory system. This system appears to detect and locate sound using both partial displacement and velocity. There are possible applications for the design of advanced sonobuoys and other surveillance systems utilizing acoustic detectors modeled on the fish hearing system.

2. Dolphin and bat hearing systems. Development of vertical resolution models obtained from the study of dolphin and bat hearing systems could lead to improved design for shaded acoustic arrays.

3. Dolphin and bat countermeasures. A better understanding of the various countermeasures used by bats and dolphins (jamming sounds, etc.) could have Navy applications.

Listed here are important areas of study which support the above lists of possible applications:

1. The development of instrumentation and techniques for studying animals, particularly dolphins, under natural field conditions.

2. The extent of behavioral theories and the improvement of animal control technologies for use in psychophysical research and general training.

3. Biological systems effectively integrate multiple sensor input for detection and classification of target objects. Investigations of the methods by which biological systems integrate multiple sensory information can lead to new techniques for the design of smart detection systems.

In addition to these areas of study there was a consensus among the members of the Sensors Group that it would be useful to generate a directory comprising the names and interests of scientists involved in studying sensors, cognitive processes, biodynamics, bionics, AI, etc. Scientists in this directory would comprise the corporate memory of information in these various fields and it would be extremely helpful to have access to their names and specialities when particular information is needed.

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NEUROPHYSIOLOGY WORKING GROUP SUMMARY

The following findings and recommendations, in brief form, represent a part of the results achieved and the values exchanged among our AI and physiology members. Neurophysiology is a broad discipline, embracing the study of functions and mechanisms of the nervous system at levels from the subcellular to the whole brain. In order to have a finite domain for discussion, we concentrated on the physiology of hearing as an exemplary area, with frequent reference, for certain purposes, to vision, touch, and electroreception in fishes. We report the following conclusions.

1. We should look across the board at defense problems, with respect to the possible contribution of new insights into how the brain works. In those cases where there is a biological system that does some task better than available machines, we should investigate that system and attempt to use its characteristics to improve equipment and methods. Two specific examples of defense problems seemingly handled better by biological systems than by machines follow:

a. Undersea surveillance is one of the most important defense areas and uses active and passive sonar and other surveillance methods. Some animal species have systems that appear to perform better than available machines as sensors and processors, at least in certain respects or conditions. The animal systems are resistant to jamming, they operate in conditions of poor signal-to-noise ratio and they can be extremely discriminating. Specific examples include the passive acoustic detection of owls; the sonar of dolphins of all seas; the sonar of the white whale in the Arctic; the echolocation system of bats; the several forms of electroreception of elasmobranchs and of electric fish; and the lateral line system of fishes; besides the visual, olfactory, infrared and other analyzing systems of the brains of various species. We emphasize the central analysis, discrimination, and localization, over and beyond the sensitivity of the sensors.

b. Communications represent an important defense issue on all levels. Human speech recognition over varied communication channels is a phenomenal achievement of the brain. Speech recognition by machine has been considered an important goal, consuming considerable funding and effort during the past 20 years with only modest results.

2. AI experts in the difficult problem of designing speech recognition devices (programs) gave it as their opinion that this field badly needs to understand more about how the living brain accomplishes this task, especially the later stages above initial frequency analysis. The limited progress referred to just above has made little fundamental advance in years and these same AI experts feel that it is now more than desirable to attempt to apply principles learned from the functioning nervous system. We do not underrate the difficulty of the task of working out how the brain analyzes speech: it will not be accomplished soon, but we believe successive stages of insight will be helpful even before a full understanding is reached. It is also clear that at least many of the stages of analysis can be studied in animal models of various species.

3. In respect to general strategy of uncovering principles of brain operation, we must point out a major need for the development of theory. This need is distinct from closely related efforts with nonliving systems. One way of labeling the special class of efforts required to understand the nervous system is theory of cooperative computation. Another aspect of strategy in neurophysiology is the opportunity as well as need for simultaneous development of experimental analysis of the living systems by the bottom up approach as well as the top down approach.

4. Beyond the recommendations on research strategy it is concluded that, while doing what can be done on the human system, and while at the same time taking advantage of simpler animal models, we should also study those highly specialized animal species that have exaggerated or developed unique abilities. It should also be pointed out that studying tissue cultures, microbes, and computer models cannot reveal how we recognize speech; to this end, an essential task is direct investigation of the brain of animals, including higher mammals, using the techniques now well developed for painless recording from the unanesthetized, fully alert individual.

5. We recommend enhanced ways and means of bringing physiologists and AI people or modeling and theoretical experts together (a) for conferences, (b) for visits to each others' laboratories, and (c) for joint research, both by established investigators and by young investigators, including graduate students.

6. Many investigators cannot afford the commercial hourly charges for access to literature data bases. We recommend that advantage be taken of the commercial offering (e.g., that by Dialog Information Services, Inc. of Palo Alto, California) of a tailored data base, drawn from the larger bases such as Biosis, Medline PsycInfo, computer, engineering and government literature, and kept up to date by the company, which the individual investigator can then search much more cheaply than the present usual method — interrogating the entire literature, data base by data base. Into the tailored data base could also be placed special lists such as names, addresses, and phone numbers from relevant directories; chapters in books, not now listed in any data base; programs of meetings, etc. Once created by an overall program covering the area of this workshop or subdivided into a few separate, tailored data bases for major aspects of the overall program, the cost per investigator would be small.

7. We recommend either a special ONR program in bionics or grants using 6.1 funds be made available, to supplement the severe shortage of research funds in these areas. Progress is definitely being held back by this research funding shortage. This applies to project grants; training of new investigators in these areas; and developing some major new techniques that require cooperation of hardware engineers, AI, or software experts and physiologists on a scale beyond ordinary grants. An example of the latter category is recording from single cells or small volumes of nervous tissue with many (20+) micro electrodes, chronically implanted in selected places in the brain of behaving animals. Whereas the techniques have been used for years, on humans as well as animals, with smaller numbers of channels, the step to a large number of channels is urgently needed and involves serious challenges for each of the required co-workers — physiologist, hardware engineer, and software expert.

8. On the level of substantive scientific questions which now need particular attention and are especailly ripe for major advance, we select the following examples, not by any means exhaustive of such a hot area:

a. What are the neural codes in the representation of sensory input at the stages of serial and parallel filtering and processing as well as in the stages of recognition, evolution, storing, switching among responses, and controlling output. How far are the codes graded, non-spike 3-D geometry dependent, chemical modulator dependent?

b. How, in detail, do divergent and convergent connectivities and hierarchical and parallel processing achieve the variety of parameter selective, combination selective, feature selective nerve cells — and how in detail are these organized, arranged, related to each other and to lower and higher levels? How far does complex feature selectivity go in small sets and how much of higher recognition depends in temporo-spatial patterns in large sets. How are subsets integrated, across submodalities and modalities? How far do repeated, partially discrete modules go in accounting for the organization at cortical and lower levels? What are the computations made in the modules, laminae, deep nuclei, etc? In what respects, to what extent, and under what conditions are the representations plastic? To what extent self-organization and is it under natural feedback or exaggerated conditions of experience? How does the system compensate for different classes of perturbations? How does it extract constancies from diverse stimuli, such as shape independent of angle of view, words independent of pitch of voice, dialect, tempo etc?

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COGNITIVE PROCESSES WORKING GROUP SUMMARY

The Cognitive Processes Working Group represented diverse disciplines ranging from animal psychophysics to artificial intelligence and expert systems. One of Minsky's immediate key points was that, as a new field, the language of artificial intelligence is evolving. Other current scientific jargons simply do not transfer directly into artifical intelligence. Artificial intelligence itself was defined as: "anything that a machine can do that if done by a person would be termed intelligent."

Licklider indicated that, up until recently, introspection about human problem solving has provided the major basis for computer circuitry design and AI programs.

Intelligence itself is too often assumed to be a single thing or process. The ability to learn information appropriate to the solution of a problem, to comprehend quickly, to draw from past experience, and to solve problems is not one skill but several. Processes involved in recall or short term memory, for instance, appear to be quite similar in humans, monkeys, dolphins, and sea lions. Intelligence in any creature or machine includes having access to a relevant data base as well as the ability to have available and to use appropriate problem solving strategies. The ability to abstract and the ability to integrate inputs from diverse sources seem to be critical elements in intelligent behavior. Diversity does not end with inputs. Although most people may never have done it, a person could, if asked, write his name with his left foot. A sea lion trained to touch a ball with its tail does that task on land even though it has only been trained to do the task in the water.

Imaging or internal representation of objects in the outer world appears to be a key process for solving problems. The formation of that representation of the outside world is dependent upon information from a number of sensory modalities. Monkeys have been shown to be able to cross sensory modalities by choosing an object they have only touched when solving the problem using only visual cues. Dolphins have been shown to solve previously unsolvable visual problems when the visual stimuli are labeled with auditory cues. Thus brains are quite capable of integrating information from a number of modalities and forming appropriate images. Computers, on the other hand, generally can easily indicate that they have previously seen some pattern, but a melody played on a different instrument becomes difficult to recognize.

Brains might be thought of as connection machines which interconnect many small organic computers — a connection machine in which each memory device has its own information processor. It's even conceivable that a brain is composed of integrated read-once store discs. Everything is stored yet the indexing and retrieval processes become quite complex.

It seems quite likely that the study of natural intelligence and the study or formation of artificial intelligence may best be served by an interactive process. The new successes in artificial intelligence should serve as a stimulus toward new ideas and hypotheses as to the nature of natural intelligence. It would, for instance be quite interesting to get a complexity theorist to look at what it takes to model what an animal does. Research in non-human abilities to make inferences and form abstractions, seems as if it might have interesting possibilities for AI application. Three approaches to AI

were described by Josephson: (1) normative — logical, decision theoretic, Bayesian probability oriented — which treats intelligence as logical analysis; (2) descriptive — using cognitive modeling; and (3) basic computational mechanisms orientation. Some generic information processing tasks involved in (3) were described: classification, WWHI (What Would Happen If), knowledge-directed data retrieval, design-by-plan selection and refinement, and means-ends analysis.

Expert systems look as if they have much to offer for solutions to various Navy problems such as the identification and diagnosis of sounds from the sea. At the same time it should be recognized that good expert systems have taken a long time to develop, e.g., eight to ten persons working for as many as 8 years to develop programs such as MACSYMA or DENDRAL, programs that do remarkable things in their specialties. Development times may decline, but outstanding programs are not readily come by.

Artificial intelligence has evolved into a broad and expanding field. There is plenty of room for new ideas. Navy needs might best be served by choosing some particular problem that holds a high priority, then exploring ways in which AI might serve to solve the problem. Intelligent creatures inhabit the oceans. The solutions they have derived may well serve as models for solving Navy problems.

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BIOMECHANICS WORKING GROUP SUMMARY

RELATIONSHIPS

Since any practical output for the bio-mechanics working group necessarily involved outputs from the other three working groups meeting here at Stowe, we attempted to formalize relationships among groups as shown in Figure 1. This Venn diagram often proved helpful, especially so in our discussions of Bob McGhee's walking machines or Jim Wilson's engineering analyses of actuator mechanisms found in the animal kingdom. The diagram speaks for itself, but we emphasize that any intelligent system (artifical or natural) will do and that the neurophysiology group perfuses the entire diagram as its wiring and/or digital transfer system.

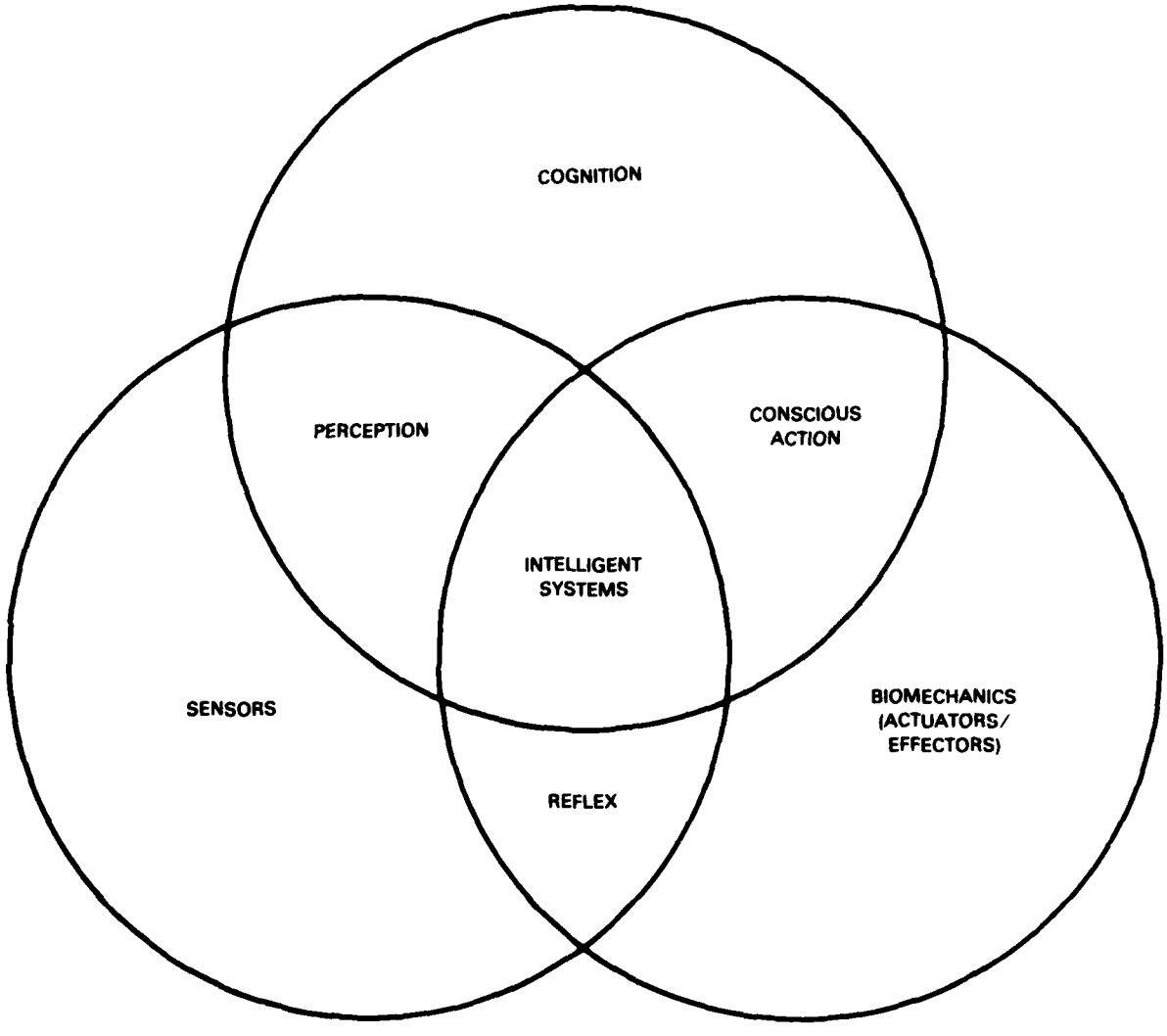
GENERAL OVERVIEW

After considerable discussion, our group outlined the entire biomechanics problem as shown in Table 1. Our basic splits were bioenergetics, biomechanics, and biofunctions. The last (required operating media) will be discussed after we've discussed the first three divisions in general and then some of their subdivisions in greater detail. The important aspect of Table 1 is that, after careful consideration, our working group has indicated (see key in Table 1) how research efforts should be directed within the overall effort. A hundred years ago our emphasis would have been directed toward materials and power sources; 10 years ago it would been directed toward means of control. The research emphasis shown in Table 1 is what we, as a group, feel is needed now.

We do not pass lightly over the problems of bioenergetics. Certainly, bioenergetics has difficult problems that remain to be solved, but to us, their solution appears assured. We may be skipping too lightly over distribution, because we later call for a distribution energy source, like ATP in a living sarcomere. What is emphatically needed is a new kind of actuator/effector that imitates biological muscle as closely as possible. Expressly not called for is yet another application of springs or pistons or solenoids or falling weights. We are looking for a truly new system of actuation.

To build such a unit, we must inspect the inventory of available materials for those properties most compatible with our intended bio-logical simulation. The same is true for possible structures made from the selected materials. Here, Jim Wilson's continuing analytical investigations of both structure and function in existing biological systems will be particularly helpful. Both the inate properties of these potential structures and their passive interactions with the ambient environment (static boundary layer conditions, etc.) must be quantitatively investigated. The ultimate goal remains clear however, a new basic actuator/effector unit.

Perfecting the basic actuator unit is clearly not enough. Whatever unit we come up with must be tested in some practical application, some complex system of basic units that accomplishes a specific task. Only through such application can we evaluate what we have done in a meaningful, quantitative manner. Only through such application can we logically approach the associated problems of control, stability, programming (navigation or specific function, for example), and dynamic environmental interaction (hydrodynamics,



NEUROPHYSIOLOGY = WIRING & DIGITAL TRANSFER SYSTEM FOR THE ENTIRE VENN DIAGRAM.

NOTE: ANY INTELLIGENT SYSTEM(S) WILL DO.

Figure 1. Relationship of biomechanics working group to other working groups.

Table 1. General overview of the biomechanics effort.

BIOENERGETICS

* Source (raw materials)
* Processes (conversion/storage)
* Distribution

BIOMECHANICS (basic unit)

** Materials (properties)
** Structures (inate, passive boundary layer)
*** Actuators/Effectors

BIOFUNCTIONS (intelligent mobile systems)

*** Test Bed for Evaluation
Control/stability/program/environmental interaction
*** Locomotion
Walking — static then dynamic
Swimming — static then dynamic
*** Manipulation
Arm and hand — static then dynamic

REQUIRED Operating Media

* Funding
* Electronic Symplasm

KEY * = noted; direct research effort appears unnecessary
** = moderate research effort required
*** = maximum research effort required

unanticipated variability, etc.). Any endeavor such as this requires quantitative feedback from the real world. We want, however, to emphasize that the group discussed only intelligent mobile systems. We did not discuss such obvious extensions as prosthetic devices with their additional control and boundary problems.

From many possibilities, we selected three systems applications as test beds for our basic actuator unit(s). Two systems involved locomotion, one operating on land and the other operating in water. Bob McGhee's years of experience with walking machines constitutes an excellent basis for an intelligent land-mobile system. Such a system should first be tested and evaluated under static conditions. For instance, McGhee's current walking machine requires 30 hp continuously just to remain standing. Obviously, our biomechanical system must do better. The system should next be tested dynamically, moving across level terrain then across rough terrain or on sand or mud. The swimming machine (either fish-like or pollywog-like) should also be tested and evaluated first under static conditions in a still pool, and then under dynamic conditions such as in strong currents or even surf. The third proposed system application was a manipulator, such as a hand-arm device. This too should be tested under static conditions (a stable platform) and then under dynamic conditions (a moving and/or vibrating platform).

SPECIFIC DISCUSSION

That completes our general overview of the biomechanics problem. Now let's look in greater detail (see Table 2) at the subelements selected for more intensive research effort.

Materials

Materials is our first consideration. We could not, of course, specify what materials, although electro-sensitive polyelectrolyte gels such as rubber do look inviting. A catalog of potential materials is an important requirement. This catalog should contain quantitative data on specific properties, with research directed toward supplying missing data. One important antibiological specification is long shelf life. Certainly, the basic unit should not be subject to rapid decay. The material must be strong yet lightweight. This property is particularly important so that the basic unit can have low inertia. The material should be flexible and compliant; it should not easily shatter or irreversibly deform. It must provide easy termination or attachability to other parts. Finally, the material must be tough. It must be capable of many bending or flexing cycles without fatigue or failure.

Structures

A similar sort of detailed catalogue must be assembled for structures, particularly structures that mimic biological systems to the maximum degree feasible. One example would be bone with its slight resilience, its external hardness, and its lightweight, sponge-like interior. The sarcomere (the basic unit of muscle) provides a second example, that of many small filaments sliding past one another, powered by rhythmically ganged electro-chemical attraction and triggered by a small change in Ca^{++} concentration. The group noted that such things as rotary actuators had recently been observed in certain flagellates and agreed that, for thoroughness, more should be learned

Table 2. Specific research requirements of the biomechanics effort.

MATERIALS
- ** Long Shelf Life (anti-biological)
- ** Strength Without Weight (low inertia)
- ** Flexible/Compliant
- ** Easy Termination
- ** Tough (many cycles without fatigue or failure)

STRUCTURES (mimic biosystems)
- *** Muscle (triggered, unidirectional power stroke)
- * Rotary (learn more)
- * Pneumatic (existence noted)
- *** Manufacture (to molecular level)

ACTUATORS/EFFECTORS (single unit, complexes later)
- *** Unidirectional Axial Power Stroke
- *** Energy Efficient
- * Direct Drive Device
- * Low Unit Cost
- *** Finely Controlled (internal misalignment detection)
- *** Distributed Energy Supply
- ** Large Dynamic Range (large force, low velocity)
- * Self-repairing or Parts Easily Exchangeable

SYSTEMS (complexes of basic actuator/effector units)
- ** Input from Telepresence, Biosonar, Bioradar
- *** Basic Elements in Antagonistic Pairs
  Assembled in parallel for force and in series for displacement
- *** Light or Electrically Triggered
  Using distributed energy supply
- ** AI Tools used to Program Systems
  to Direct Assembly
  to Define and Test Controls
  to Evaluate and Modify Systems
- ** AI Tools used to Program Systems
  for Global Solutions
  for Probing Solutions
  for Script Solutions (missing information)
- *** Isoparametric Evaluation
  Explicit feedback of info/needs to AI community

KEY
- * = noted; direct research effort appears unnecessary
- ** = moderate research effort required
- *** = maximum research effort required

about these systems. Pneumatic systems, such as those found in the legs of some jumping spiders or in the proboscis of nemertean worms, were also listed for completeness. However, since various pneumatic systems have been extensively applied by engineers, nothing truly new was expected from this approach. The manufacture and/or assembly of the basic unit did appear to require intensive research since it seemed probable that such might have to be accomplished at the molecular level.

Actuators/Effectors

As said earlier, the actuator/effector should be truly new and as muscle-like as possible. It should be emphasized that the working group expressly did not try to invent such a basic unit. In fact, we had to be constantly on guard to prevent insipient invention in the spring/piston/bellows/falling-weight school. It must also be noted that the specifications employing complexes of these units will follow later. We were all agreed that the unit should, like muscle, provide only a unidirectional, axial power stroke. The unit should be energy efficient. As a criterion of such efficiency, we chose that of muscle, viz. 25% minimum with a possible 45% maximum. This upper limit could, of course, be exceeded without dismay. The basic unit should be a direct-drive device (no linkages) and should also have low unit cost. Again, McGhee's experience provided a cost criterion. Currently a single "leg" on his hexapod costs $100K. We would be competitive if we could produce a biomechanical leg with the same operating capabilities for less, hopefully considerably less, than this figure.

The actuator/effector unit should be finely controlled, i.e., it should contain internal misalignment sensors. The major approach to fine control would, however, be through having many individually activated units. The basic unit should, like muscle, have a distributed energy supply. This energy supply could be refurbished after each firing; however, the attendant energy distribution and storage problems were not probed in depth. The unit should have a large dynamic range. Expressly it should be able to develop large forces at low velocity. Much of the energy loss in conventional actuators results from the use of inertia to generate force and of braking to control force. Finally, if possible, the basic units should be self-repairable, or failing that, parts should at least be easily exchangeable.

Systems

Lastly, we come to the evaluation of the whole biomechanics effort through the assembly of basic actuator/effector units into a limited number of intelligent mobile systems, viz. a walking machine, a swimming machine, and a manipulator. In these, not only is the basic unit put under critical test, but the whole complex of control, stability, programming, and environmental interaction must be met and solved in a meaningful way. Again, the group expressly avoided any attempt to invent these systems during our 3-day deliberations. Jim Wilson's engineering and mathematical analyses of various actuator systems extant in nature provided the group with most challenging ultimate goals. The elephant's trunk, an apparatus composed of some 40,000 muscles and weighing about 300 pounds, can lift and toss weights in excess of a ton and also crack the shell of a peanut without damaging the meat. The squid, Liligo pealei, in capturing prey, extends its tentacles about 50% in 15 to 30 miliseconds, a time practically imperceptible to the human eye. Wilson

has good diagrams of the transverse, longitudinal, circumferential, and helical muscle systems that make the squid's performance possible. These, though, are the ultimate challenge; we must content ourselves with far more mundane initial objectives.

The basic approaches to systems development laid down by our working group were as follows. Dave Smith's extensive experience with Navy telepresence equipment was recognized as a valuable information source for systems development. NOSC's broad experience in biosonar and bioradar research also provided essential expertise for sensory devices associated with such systems. The actuator/effector subassemblies were to be operated as antagonistic pairs. This statement in itself introduces a significant reseach challenge, i.e., as one subassembly delivers its power stroke its antagonistic partner must sense that movement and allow itself to be passively extended. Our decision thus highlights an intricate sensing and control problem, which is precisely what the systems application effort is supposed to do. The basic actuator/effector units will be assembled in paralled to achieve desired force and in series to achieve desired displacement. The units will be light or electrically triggered and will then complete the power stroke, like living muscle, using an energy supply already distributed within the unit. The use of solitons, espoused by Forrest L. Carter for many switching applications, is certainly another control/triggering possibility.

The group identified several active links between its effort and those of the AI community. Most importantly, their symbolic languages, such as SCHEME, would be used to model systems applications concepts before any such system was attempted in fact. When reasonable systems specifications have been worked out on the CRT, then these same symbolic tools will be used to direct system assembly, to define and test its control, to evaluate system performance, and to design and test necessary system modifications indicated by those evaluations. Such symbolic modeling will decrease development costs while at the same time increase its precision.

AI tools will also be used to program application systems to do specific things. We envisioned three generic types of programs: those providing global solutions (like mapping a course from points A to B around obstacle Q along the route), probing solutions (like checking obstacle Q for any unmapped features), and script solutions (like using what's known in advance about obstacle Q's characteristic behavior to fill in missing information). Again, we will use Wilson's analytic observation of natural systems to assemble a catalogue of detailed scripts. It is important to note that our systems evaluations will be isoparametric. Natural systems always optimize design for a particular purpose at the expense of efficiency in other areas. We must, therefore, do careful research, using natural systems as a benchmark, to assure that our measurements are correctly designed to rate the particular feature under evaluation.

Our working group was certain that the biomechanics effort would provide strong feedback of basic information and of further needs for tool development in the AI community. We hoped that they would heed our feedback, especially regarding desired new tool development. This last was based on our certain knowledge that we'd have our hands full with our own problems.

REQUIRED MEDIA

Finally, the required operating media for this biomechanics effort needs specific comment. The matter of funding is important. The amount of the funds is negotiable and needs little discussion here. For so much, we can provide so much, etc. It is the manner of funding that is vitally important. Whatever the amount may be, the funding must be nonintermittent over an extended period, say 10 years. There is no sense in embarking on an effort of this difficulty and magnitude with an intermittent or uncertain funding arrangement. That way lies waste, frustration, and failure. Nonintermittent funding, therefore, is a requirement.

Secondly, our group definitely wished to continue as a working group. Through DARPANET, this desire is easily made a reality despite the large geographic separation between various group members. Electronic mail is a very effective means of keeping scientists in interactive touch with the exhilaration that results from such contact. Our group resolved to establish appropriate DARPANET linkages to all members, to form an electronic symplasm, or virtual biomechanics center, if you will. It was also pointed out that such electronic linkage among a geographically distributed group of scientists has many hidden advantages. Each separate member is constantly exposed to differing research or knowledge environments. If they are then efficient in exchanging the information gained, the group, by means of that exchange, has vastly increased its effective size and expertise.

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APPENDIX A

INDIVIDUAL SUMMARY STATEMENTS BY PARTICIPANTS

This appendix contains statements by individual working group participants. Each statement is presented alphabetically by participants' last name within each of the four working groups.

The chairmen of the four working groups gave all participants an opportunity to make statements. The feeling was that these statements would greatly aid each chair in preparing the required working group summary. Some participants did not prepare statements. However, all statements received are presented here.

These statements have been reviewed and corrected by each submitter. Because these statements represent personal and professional opinions and writing styles, we have kept editing of them to a minimum.

INDIVIDUAL STATEMENTS BY SENSORS WORKING GROUP

RICHARD ALTES
ORINCON CORPORATION

Topics that should in my opinion, be emphasized:

1. Use of biological models for multisensor integration.

2. Need for biological models of pattern recognition, and use of pattern recognition theory to predict relevant features for biological sensors. Interaction between pattern recognition theory, psychological experiments, and neurophysiology via a group of people (perhaps at difference institutions) who are paid to interact and report joint progress.

3. Learning in:

   (a) Biological systems (psych, models and neurophysiology correlates)

   (b) Bayesian classifiers (e.g., detection)

   (c) AI systems

CARTER COLLINS
SMITH KETTLEWELL INSTITUTE OF VISUAL SCIENCE

It appears we may have sufficient sensors. We need methods to extract (abstract) further, higher level information from sensors (and sensors arrays), particularly the identity of the target object (in addition to its three dimensional coordinate location). In addition to the excellent detection schemes existing we could add further AI processing principles. To achieve recognition (for instance) in real time we should keep the algorithms as simple (minded) as possible---this will help impedance match our methods to the capabilities of the early systems.

The higher level products of recognition (the identifications) should be represented in a three-dimensional world model as perhaps the names of the objects, each with its own linked list of attributes, e.g., XYZ coordinates, size, color, type, velocity, special markings, etc. At this level (of the world model) each of the sensory modalities could communicate. If one mode "sees" an object, another mode could check that location (further) to corroborate.

We probably have adequate tranducers.

We need to know more about:

Pre-processing raw information from a transducer to derive higher level abstractions about the nature and indentity of the object detected — in real time.

We need to know how to better cross-reference an object detected and classified by one sensor system with (perhaps the same) object determined by another sensor system.

We should at least dedicate a separate microcomputer to each sensor (or group of sensors detecting the same physical quantity). This computer's sole task would be detection of the location and identity of the targets it picked up.

These higher level constructs would be fed to the central host computer for integration into its world model, arbitration of disparate identities between sensor systems, and decision of action.

Addressing the specific questions for the Sensors Group:

1. Accommodations in the conceptual framework should include knowledge of the transfer function of each sensor, including gain, zero offset, and nonlinear characteristics. The world model of the intelligent system should include awareness of the absolute background (or baseline) levels of each measured variable in the environment from which to add or subtract (i.e., integrate) changes detected by the sensors.

The conceptual framework describing relationships between specific sensors in the intelligent systems should see each sensor (system) as a facet or

window looking at the real world from a different point of view. These various views should come together in the world model of the system, which would be the best representation of what the system thought the world looks like.

After detecting edges of objects and describing them mathematically (as a means of data compression and convenience for comparison), the combination of edges can be compared with a dictionary of known object concepts (in the knowledge base) to identify unknown detected objects.

It is these identities that are entered in the world models, each at its own three dimensional detected location. Perhaps each sense (combination of sensors for the same physical quality) should construct its own world model, and the higher level host processor could choose, arbitrate, and best decide what is <u>really</u> at each location by comparing what each sensory subsystem passes up to the host with what each of the other subsystems offers. This would be the mechanism for implementing relationships between sensors. Feedback from the host to a given sensor system could perhaps modify that sensors processing (is that really what you see?).

2. Energy and information transformations found in biological sensor systems of particular value to artificial sensor systems are the nonlinear and derivative nature of sensors and the integrative (information restoring) nature of the central processing system.

a. Nonlinearity, i.e., logarithmic (constant percentage) response permits an extremely wide dynamic range of information transmission over a limited bandwidth channel, i.e., (1) reduces the bandwidth required and/or (2) increases the resolution of the measuring system.

b. Dual (or multiple) sensors of markedly different sensitivities can increase the dynamic range by many orders of magnitude (perhaps using different physical principles or methods of fabrication for sensing the same variable).

c. Sensors systems responding only to changes can <u>interrupt</u> the main processor only when there is something different to consider — otherwise they will remain quiet. This can relieve the overall system (CPU) of much petty redundant and unnecessary I/O processing and thus free the system and provide more processor time for higher level decisions. The system can automatically be "smarter" using derivative imputs. The philosophy is "if it is the same as last time I looked, I don't want to hear about it, don't interrupt me — only let me know about something new — then I'll take time to consider it, i.e., integrate it into the overall picture. Even then it may or may not have relevance to the present task (or overall homeostasis), so I may consider it further, at a higher level only if appropriate." This can also be called "adaptation" to constant stimuli — an adaptive process.

d. The central processes should then be integrative, i.e. DC — restore the derivative (differentiated, AC coupled) input information to keep a record of the absolute level of each physical variable of the environment in its world model for reference and interrelation to other inputs.

e. The peripheral sensors should also respond to over or under limits (e.g., burning or freezing noxious stimuli) by interrupting the central system.

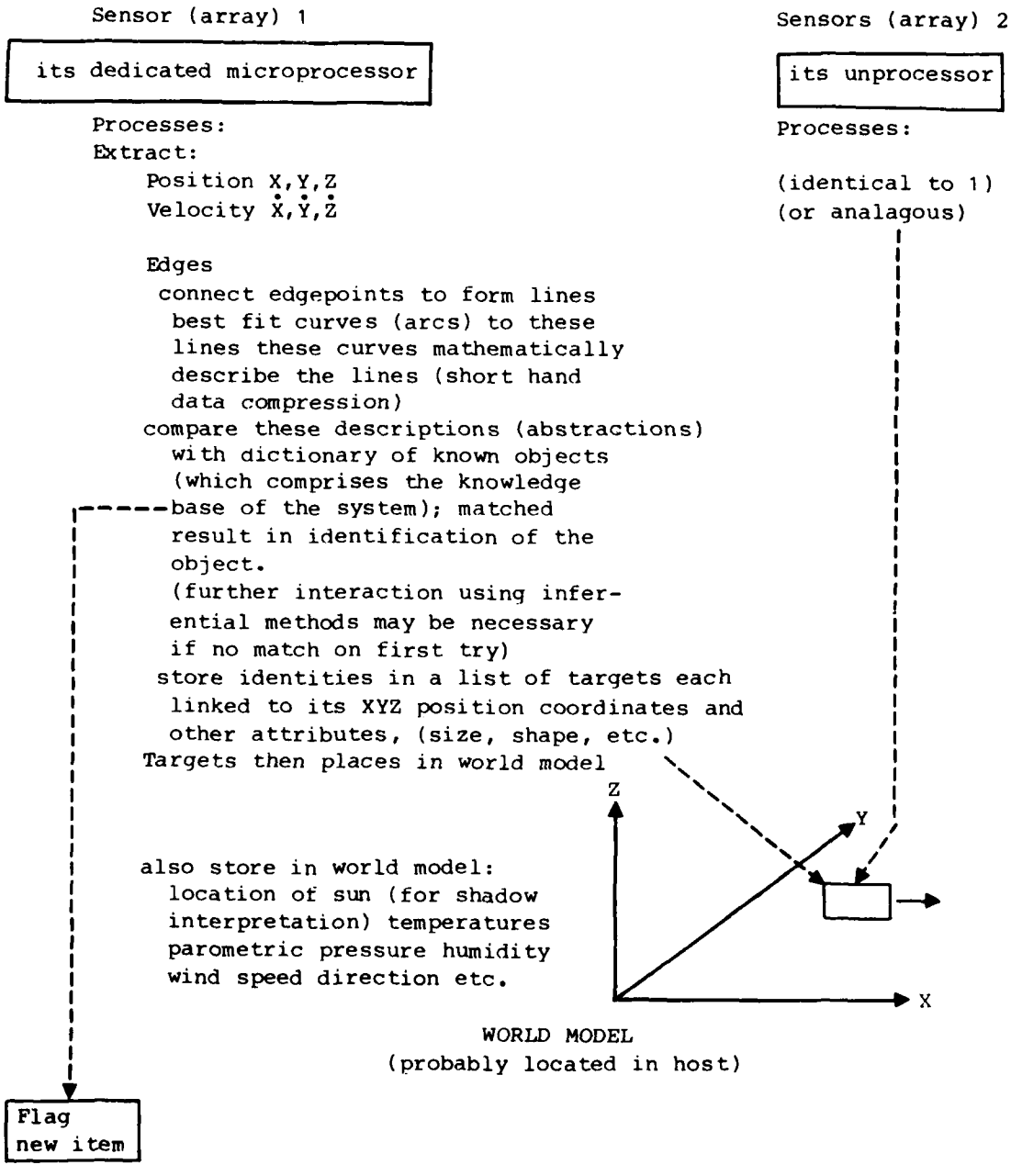
3. The short term prospects for parallel processing are excellent. Microcomputers are cheap, easily implemented and can and should offload the host processor of I/O information processing tasks. The biological model processes inputs at the peripheral level, we should emulate this form of intelligence. There is much preprocessing to be done on the raw information for each sensor and it should logically (as biologically) be done peripherally. Each sense can be represented by more than one sensor, perhaps arrays of sensors which would certainly require their own preprocessor. Even one sensor can supply a rich source of information when fully supported by efficient and sophisticated processing software. For example, an AC air pressure sensor (microphone) can alone use a full fast and powerful microprocessor for interpretation of sounds (squeaks, rattles, tool contact slippage, impact location of a tool, ticking of a fuse, movement for restored joint or thread, or hull; characteristic movements of other divers (to help identify them), etc.; not to mention voice analysis, motor or engine malfunction noises, enemy fire location. This kind of processing should be done peripherally in parallel and the central host processor informed only of results (or inability to recognize the sound). This kind of peripheral information processing software constitutes a major project in itself — a branch of AI. Certainly the host computer won't have much time to "think" about much else if it has to process input sensor information at this level of complexity. The major task of the central host should be (at the cerebrial level) integrating the <u>results</u> of this type of preprocessing deciding what it means, deciding what to do about it and then the outputs, in an integrated fashion, directing (i.e., orchestrating). Even the output coordination and control (brainstem, cerebellum and reflex levels) should be offloaded onto other I/O processing microcomputers. Each process can be adequately performed serially in each processor using conventional software techniques today.

Distributed I/O processing, each separate c preprocessing and uploading <u>is</u> parallel processing — controlled by host processor as a system. Different from multiprocessing in which one machine timestores.

Total system performance can be dramatically increased by employing the biological model of parallel processing. We can readily afford a separate microcomputer for each sensor (or at least each sense) and in some cases more than one processor per sense — for example, a separate processor for interpreting verbal input and another processor for interpreting all other sounds. This second processor might distinguish and recognize types and locations of sound sources such as where you dropped that tool (stereo, 3-D, spatial processing), is that vehicle a half-track or truck? what was the projectory of that rocket? This kind of information would then be available to the host processor responsible for integrating the inputs, adding newly acquired information to the world model, and deciding possible courses of action. If a teleoperator, the central host controller could aid in coordination of outputs; if autonomous, it would choose and initiate an appropriate course of action and direct and orchestrate the outputs. The actual coordination of each output (bio)mechanical effector should probably be handled by a separate processor for each output (analagous to cerebellar and spinal ganglea control coordination).

4. A knowledge representation system for modeling sensory systems should depict three-dimensional spatial representation with other characteristics such as temperature, color, brightness, and movement attached to each object. Sun and cloud positions, wind direction and velocity, humidity, barometric pressure, visibility, and pollutants (air contents) should all be included.

A Possible Process Model



HOST PROCESSOR

Integrates target and all other information, may feedback to sensor systems to narrow their search areas etc., or to request confirming information. Controls both forward and backward. Decides on course of action and displays, announces and/or controls outputs.

RICHARD R. FAY
LOYOLA UNIVERSITY OF CHICAGO

The benefits to me from the conference have been:

a. A better understanding of the goals of AI, bionics, and expert systems as applied to the goals of the Navy, and other organizations with problems to solve.

b. Understanding more of the nature of specific applications to which basic biological research may contribute.

c. Understanding the structure of Navy R&D organizatons.

d. A better feeling for the breadth and depth of the AI-bionics scientific community. Who they are, where they are located, how many they are, the scientific disciplines involved.

e. A chance to meet and have extended discussion with others in my immediate field (sensory neuroscience), and a chance to meet those in other fields and to see possible relations and collaborations among fields which may be profitable for advancing AI research.

f. The better definition of a broader context, including applications, into which my own research may fit.

Some of the issues which have come out of the meeting and which are relevant to my own concerns are:

a. Funding. If research on biological systems may have benefit for further development of AI, bionics, robotics, short term goals are not easily and directly relatable to specific problems and their solutions. They are part of longer term and more general problems for which a funding mechanism should exist.

b. I think that at present, very few specific and testable models of brain function (at a physiological level) exist. This is due in part to a tendency in neuroscience to focus at the molecular and membrane level, and to put off work on how restricted sets of neurons may solve information processing problems through this interaction. If more work were focused at the level of cells, aggregates of cells, and neuronal networks and systems, more sophisticated models of neural processing would emerge. These could then be used to help specifiy the architecture and structure of artificial systems which may solve the same processing problems.

c. One of the important places to concentrate energy and activity in biological research is on the transduction of physical information, the encoding of this in patterns of neural activity, the transformation of these codes, and the decision mechanisms used to operate on these transformations. This work should be carried out on different sensory systems and in different species (varying in structure and complexity). This will provide a broad biological context and data base within which any specific system (biological or artificial) may be better understood.

d. At a very specific level, I see potential application for the work I am presently doing on the acoustic o-lateralis systems of fishes. This includes a number of transducers including hydrodynamic flow (velocity and displacement) detectors; the lateral line neuromasts, particle acceleration detectors — the otolith organs acting as accelerometers; and sound pressure detectors — the otolith organs coupled to a pressure transducing impedance discontinuity. This system is capable of measuring near-field particle motion direction and amplitude, near-field pressure magnitude and phase, and far-field pressure and particle acceleration quantities including amplitude, direction, and phase. It appears that animals use this combination of receptors to create an image of the local acoustic environment (in the range of several meters), in a bandwidth of about 1 Hz to 1 kHz. While we know that the detectors transduce these physical quantities (with a sensitivity down to -40 dB re 1 dyne/cm2 and to 0.1 nanometer), and that phase is preserved in the neural code, we do not yet know if and how this information is combined across organs to form an image.

Neurophysiological research on the neural mechanisms which deal with this information, combined with behavioral research on the uses to which this information is put may describe a very efficient and possibly ideal system for short range acoustic imaging underwater which could possible be simulated by artificial systems.

BRUCE P. HALPERN
CORNELL UNIVERSITY

The interchange between the various groups was beneficial and stimulating. I was struck by the need for two things:

1. Immediate goals should be stated as a problem, rather than as a need to improve technology. For example, "We need to locate non-USA submarines" is a problem statement, while "How can sonar be improved to locate submarines better?" already assumes the technological solution. For the general problem statement, chemical signs, electric field changes, magnetic changes, alterations in behavior, or grouping of marine organisms because of chemical, electrical, acoustic, etc., output of a submarine, might be suggested.

2. The ultimate basis for, and criterion for success in, sensory areas, is what living organisms can already do. For speech recognition, this is perhaps so obvious that it's forgotten. For aquatic mammal ranging, locating, and identifying behavior, little is known of what they really can, and do, do under field conditions. Studies which combine careful physical measurements of the acoustic, thermal, chemical, and electrical marine environment with thorough observation of behavior (motor, acoustic, etc) under field conditions are badly needed at least for dolphins.

AD J. KALMIJN
UNIVERSITY OF CALIFORNIA, SAN DIEGO, CALIFORNIA

My question was: What is AI about in the mind of the other participants. I sure got my answer.

My assertion was: We should include research on the primarily aquatic sensors for the detection of electric and hydrodynamic fields. I am glad that this assertion has been accepted by both the sensors and the neurophysiology chairmen in their final statements.

The time-proven electric and hydrodynamic field sensors of fishes are expected to be simpler and more tractable, but at least equally, "good" as the more sophisticated sensors of dolphins, bats, and men.

The electric and hydrodynamic sensors characteristically operate in the near-field at high precision, and are little affected by far-field interference. They look at principally different physical stimulus features than the far-field detectors do.

The near-field systems are uniquely accessible for systems analyses, having a finite number of detection channels with their input terminals right at the skin surface of the animals. The stimulus fields are, with new technology, now readily measured as well.

Moreover, behavioral experiments to determine the animal's use of these sensory systems are easier because of the more reflex nature of the responses.

Studies in progress will greatly benefit from this workshop. I thank the organizers for inviting me!

CAMPBELL L. SEARLE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

I am not sure whether I personally or we as a group addressed the issues that the Navy was primarily interested in, but from my perspective this was a very useful conference. I was able to interact with many people who I had not met before at professional conferences. Drs. Suga, Merzenich, Konishi, and Yin, for example, do not normally attend meetings of the Acoustical Society, because so little of that meeting is devoted to physiology. I have been concerned for years with issues which cut across the disciplines of electrical engineering, artificial intelligence, experimental psychology, and neurophysiology, as these disciplines pertain to auditory perception and speech recognition. This was the first conference I have ever attended where such a broad range of disciplines was broadly represented, and where there was a flexible enough agenda to permit interaction across all boundaries.

There was general agreement between the speech people and the auditory neurophysiologists present at the meeting concerning the importance of neurophysiology to automatic speech recognition. But it is important to understand that despite our unanimity, this is not a widely-held view among speech researchers. Most groups working on speech recognition have paid no attention to auditory physiology or psychophysics.

My only concern, as noted above, is that the objectives of the Navy were defined only vaguely, hence were not directly addressed by the group most of the time. The need to continue support of basic research was clearly articulated several times, and I certainly support this concept. There were requests that we discuss specific areas where Navy support should be concentrated. This is hard to deal with objectively in a diverse group. The natural response is "Give the money to my specialty, and take it away from others." There were also requests for discussion of areas where biological systems are superior to existing military systems to perform some specific task. This too is hard to deal with in a diverse group, because many of the academic types like myself are not familiar with the present state-of-the-art in military systems. This question can best be answered by direct discussion between a Navy representative and an appropriate academic, familiar with the particular area. I certainly would be willing to discuss technical issues in my narrow range of expertise in such a context if that would be helpful.

WILLIAM R. UTTAL
UNIVERSITY OF MICHIGAN

Obviously, there is a community of people with common interests currently developing (for some years now) with a conceptual core focusing on the processing of information by natural and artificial systems. Ideas are flowing forwards and backwards among computer, biological, psychological, and engineering types, but no subfield is likely to provide a unique key to development in this field. The symbiotic interaction among these sciences, however, is working to produce considerable progress. Progress is likely to continue but there are some problems. Premature demand for complete solutions to practical problems may lead to disappointments in both the applied and theoretical research communities. Overattention to immediate needs may divert important resources from needed fundamental research in math, biological and waste engineering talent and energy.

An overall analysis of the generic operations performed by natural and artificial systems is badly needed. Fragmentation is ubiquitous in the field nowadays. Considerable duplication occurs because no functional taxonomy exists to hightlight essentially identical tasks and goals.

Specifically, work should be channeled (in my opinion) into combinatorial theory, parallel design for signal processing, sensory materials and devices, and psychophysical and physiological system analysis in order to develop an intellectual superstructure to organize and coordinate the entire field. There are many logistic, philosophical and theoretical issues to which attention must be paid in order to make further progress. A considerable mythology exists concerning past and present successes of both AI and neurophysiological modeling that deserves considerable scrutiny. The field is still searching for a philosophy, definitions, and general points of view. The limits of the reductionistic approach (from behavior to neurons and logical gates) should be considered in detail.

INDIVIDUAL STATEMENTS BY NEUROPHYSIOLOGY WORKING GROUP

MICHAEL ARBIB
UNIVERSITY OF MASSACHUSETTS

Probably will not simply "plug in" biological solutions to build useful machines. Rather, biological study widens the search space, e.g., as we understand the range of adaptations of the auditory/lateral line/echolocation system to different ecological niches.

Claim: Close to periphery (e.g., auditory, visual, echolocation, tackle), models of biological systems may help design of AI system. For high-level systems, AI will offer more than biology to system design--but biology may provide metaphors of cooperative computation of multiple subsystems with incomplete, inaccurate knowledge to complement AI concepts of knowledge representation, search, expert systems, etc.

AI needs more work on learning, and can learn from studies of neural plasticity, habituation and facilitation, corneal reallocation.

Action-oriented Perception: Analysis/design of perceptual systems should be more closely coupled to crisp functional specification of the behavioral repertoire that perception is to serve.

ALISTAIR D.C. HOLDEN
UNIVERSITY OF WASHINGTON

ARCHITECTURES FOR ADAPTIVE, INTELLIGENT SYSTEMS

This is a summary of the perceptions of someone in AI of some areas of research which should be pursued in the AI/bionics field. Three days of discussions with neurophysiologists have contributed to these views.

NEURAL NETWORK MODELING

Twenty years ago there was a Bionics conference sponsored by AFOSR in Dayton, Ohio, and numerous papers were presented with models of neural networks. Because so little was known then about living nervous systems, there was much criticism that the models were not representative of the real world, and this area (neural modeling) was abandoned by many workers. There is now, however, enough experimental data from much painstaking neurophysiological research, that neural modeling should be encouraged, with the emphasis on (a) modeling what is known of perceptual systems (such as the dolphin and bat's sonar, the auditory systems in general, the songbird's acquisition of its song, the owl's ability to quickly and precisely locate its prey, etc.); (b) the creation of models of subsystems which are frequently encountered and frequently used as building blocks (e.g., simple layers with lateral inhibition, feature-mapping layers, cross-correlation, etc.) and, particularly, structures which are regular (e.g., retinal structures); and (c) the design of architectures which interconnect the simpler subsystems to produce systems which exhibit interesting behavior.

The simplest systems should be tackled first (in the time-honored, bottom-up approach proposed by Francis Bacon) with the expectation that more complex systems will contain instances of the more primitive, simpler systems. The design of these architectures should be guided first by known physiological connections but also by hypotheses which could explain behavioral characteristics. This approach could lead ultimately to a systematic study of intelligence. The work described by Pribram at the workshop suggested a hierarchical model for cognitive learning with lower level processes such as motor and sensory processes leading to "automatic skills," and "episodic" skills leading to the use of "content" to transfer skills to other situations, etc. Neural network architecture could be devised with progressively higher intelligence. Such modeling would, of course, be verified using experimental data, and could suggest some new experiments.

SPEECH UNDERSTANDING

Impressive results have already been achieved in speech-understanding by machine, but much remains to be done before we have machines which can cope with large vocabulary, continuous speech in a noisy environment, with many speakers and no pre-tuning to each speaker. It should be realized that the problem of natural language understanding is a subset of the speech problem. The latter provides input to the former and, no matter how sophisticated the

pre-processing system is, speech processing will produce sequences of "unreliable" phonemes for use by the NL analyzer. Speech recognizers typically overcome the problem of unreliable phoneme recognition by using syntactic constraints, in particular, and semantic representations, which use "context" (or scripts), "frames" (conceptual dependencies), relationships (semantic network), etc., to resolve ambiguities, provide expectations, and avoid interpretations which make no sense. (It is interesting to note that there are innate syntactic recognizers built into songbirds which allow them to learn the song of their species.)

There is a need to continue investigations into auditory systems at the peripheral level, but, even more, work is needed at the higher levels. It is further suggested that speech understanding systems (SU's) could well incorporate the methods used for speaker identification. This would allow the SU to use the first sentence or two to establish the lower level features and co-articulation habits of a particular speaker, and pre-tune the recognizer to the individual speaker. Also, the prosodic features related to emphasis (linguistic stress) should be used to (a) establish phonemes which have been reliably recognized, and (b) allow modification of the speech data to remove the effects due to emotional state, etc. (i.e., normalization).

ARTIFICIAL INTELLIGENCE

From the practical point of view, it is unrealistic to expect that our knowledge of natural systems will lead in the near term to intelligent systems. The latter will inevitably come from basic AI research, where any method which can be devised is brought to bear, using the highly limited resources available in even the biggest and fastest computers. The work in Knowledge Representation (including semantic representations, meta-knowledge, etc.), Inference, Searching, Learning, etc. is making steady progress. Also, the current interest in "expert system" development, where any problem (e.g., real-time control, theorem-proving, engineering consultant, etc.) can be effectively solved by trickling human expert knowledge into interconnected sub-expert systems. (The interconnections themselves are also "expert systems" and are formed from "production systems," augmented transition networks, etc. The basic requirement is that human knowledge can be easily added incrementally, without re-programming so that during operation the system can be continuously improved.) Sophisticated systems of this kind (a) allow the addition of knowledge about problem-solving strategies and meta-knowledge, in general, to be added; (b) can advise the human expert on the ramifications which will result if he adds a proposed new rule; (c) can resolve conflicts between rules; (d) can generalize rules; (e) can communicate with both the expert and the user in a subset of natural language, (f) can execute efficiently; and (g) can make model of the future human users of the system. Much more work is needed in the seven areas mentioned above.

MARK KONISHI
CALIFORNIA INSTITUTE OF TECHNOLOGY

Biologists are engineers who study the design features of machines called animals. Animals are finely engineered special purpose machines. Their control mechanisms lie in the nervous system, which is composed of building blocks called neurons. Neurobiologists want to understand how animal machines operate in terms of connections and signals between neurons. Although much is known about neuronal connections and signals, little is known about how the nervous system encodes information. Neural codes are the language for all transactions in the nervous system. What is the logic used in neural coding? Animal machines are much more flexible or perform certain tasks much better than man-made machines. Are these differences due to differences in the materials used (neurons versus transistors) or in the logical procedures used?

The main aim of AI research, as I understand it, is to construct logical scheme (be it on paper or in a computer) for solving a particular problem. Thus, to understand the logical schemes of machines designed for solving problems is the common goal of AI and biological researches. Interaction between these two groups of scientists should be very desirable for the following reasons: 1. Exploration by AI researchers of logical procedures for solving a problem clarifies the problem and methods of its solution. Biologists can learn to work with specific hypotheses. (Hypothesis testing is rare in neurobiology.) 2. Biological machines are already there solving problems in which AI researchers are interested, for instance, pattern recognition.

As to this conference, I thought it was very interesting and successful both at the level of personal encounters and at the level of collective discussions. I wished that I could go to other groups more freely to sample what they were discussing. I think that occasional meetings among the disciplines represented at the conference will be beneficial.

RICHARD F. LYON
FAIRCHILD RESEARCH CENTER

In the neurophysiology group, a number of us began a new productive collab-oration between neurophysiologists and practitioners of the artificial sciences. We came to understand how we could better communicate with each other, and share knowledge and ideas, through models.

The key to this successful start, and to continued future synergy between us, is the development and elucidation of models that people on all sides can understand; developing the shared terminology and concepts for these models will be nontrivial.

Some of us believe that the prevalent mathematical and psychological models, both descriptive and analytic, are inadequate, and do not really promote very much interdisciplinary understanding. The new alternative is to use computational models; that is, running computer algorithms that mimic the performance at the systems being modeled. Then whether or not these models can be "understood," mathematically or psychologically, they can be instrumented as biological systems are instrumented, and thereby can be compared with biological "reality."

In the field of auditory neurophysiology, good modeling results have already been obtained by researchers from both the biological and artificial camps. Early neurological models of binaural interaction and pitch perception were actually proposed by psychologists (in 1948 and 1951) and have now been largely verified physiologically, and mimicked by computer. Much more work on aspects of hearing will be needed before we learn enough about hearing to make competent machines to listen to speech, sonar etc.

An important aspect of the necessary future work is continued neurophysiological research on specialized sensory capabilities such as those of bats, owls, electric fish, etc. Studies of exagerated capabilities, and comparative studies, have made trememdous contributions already. Aggressive computer modelling of these capabilities must also be supported.

None of this sounds much like AI, but we should recognize that this field is becoming increasingly diverse, in studying many artificial approaches to problems previously only solved by biological systems, irrespective of "intelligence."

Particular sorts of models are deserving of special attention. In the auditory field, for extraction of features related to time patterns and time relationships, auto- and cross-correlation array models seem widely applicable, and are definitely now found in cortical maps. The notion of correlation as a functional module, from which many useful operations can be constructed, seems quite powerful. Secondly, models of automatic compensation, stabilization, optimization, and self-organization are needed at all levels, in all sensory modalities. Generally applicable techniques or modules have not been found for such tasks.

All this research makes tremendous demands on computing resources. Many good models go unimplemented, or are inadequately explored, due to severe

shortage of computing. To alleviate this, we should proceed with development of high-performance VLSI-based specialized architectures for modeling, as we at Fairchild are doing with the MSSP machine for speech modeling research.

M. M. MERZENICH
UNIVERSITY OF CALIFORNIA, SAN FRANCISCO

A FEW GENERAL CONCLUSIONS

1. A new class of speech analyzers-recognizers could be modeled using principles of auditory physiology (coding), initial processing ("decoding"), feature extraction, representation, and recognition. Relevant sources of physiological information include: (a) 8th nerve "mapping" of the representation speech elements and other complex signals (e.g., Sachs, et al.; Delgutte, et al.; Kim, et al.); (b) definition of relevant codes re speech as they bear on CNS decoding (e.g., Goldstein, et al.; Loeb, et al.; Sachs, et al.); (c) nature of brain stem "feature extraction" (numerous studies); (d) nature of higher order signal processing and representation (Ehret, et al.; Knudsen, et al.; especially, Suga, et al.); (e) growing understanding of the nature of processes underlying the origin (self-organization), maintenance, and adaptability of forebrain representations (e.g., Merzenich, et al.).

2. While there has been a tremendous R&D effort in development of speech and signal analyzers and recognizers, there are only a handful of neuroscientists studying the neural bases of coding, analysis, representation and recognition of such signals in the nervous system. Information crucial to development of bionic models is being generated piecemeal, and at a painfully slow rate.

3. Over more than 20 years, Bell Labs, IBM, et al. have not, despite incredible effort and expenditures, developed speech analyzers and recognizers comparable to the human machine. Development has peaked out. Give bionics a chance!

4. I have been working on "bionics" projects (neural prostheses) for about 10 years, and am intimately familiar with more than 20 such R&D projects. In my opinion: (a) Efforts dominated by AI-engineering almost never really succeed. As a rule, their constructed highly sophisticated devices don't do the right thing. (b) Efforts centered in medical and physiological groups with limited engineering almost never really succeed. The correct device principles (when they are understood), are, as a rule, poorly dealt with by developed devices. There is usually little understanding of requirements for a practical, manufacturable device.

To state the obvious, in bionics research of this kind these disciplines must be (a) married, and (b) approximately equally weighted. At present, there is a great imbalance toward AI and engineering in this R&D area.

A common problem: Excellent engineers hire a neurophysiologist who is a hack (and vice versa).

5. Self-organizing model representational and recognizing systems could now be constructed using a bionics approach. Such modeling should be undertaken.

STEPHANIE SENEFF
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

This conference has been a wonderful opportunity for me to expand my horizons on at least three fronts: acquaintances, knowledge, and perspectives. I feel that I now have a number of new friends in diverse fields, some of which I had previously felt were of no relevance to my work. Through this conference for example, I have become aware of how important the study of specialized animals can be towards the goal of understanding human auditory processing. The certical representation of bird songs may not be all that different from the certical representation of the speech signal. The tremendous advantage of the former is that we can hope someday to characterize it fully enough to believe we understand it. Generalization may then lead to the largest truth of speech decoding, and then, from the engineer's standpoint, better speech recognition devices.

Now that I am acquainted with a number of professionals in the field of neurophysiology, I would consider the idea of attending a major conference in that field. One problem with research is the kind of isolation that occurs because of specialization. One of the most important aspects of the workshop is the cross-pollination. The workshop has opened the door to neurophysiology a crack, so that now I can dare to venture inside.

The specific bits of knowledge that I have acquired have been delightful gems that entice me to know more. I am particularly delighted to see that biologists are beginning to use computers to build models of what they see. I view such computational models as the focal point of the workshop, the meeting ground for the engineers and the biologists. Both sides can benefit from the response to the other. For example, the biologist's concern is whether the model fits the data for the particular neuron or collection of neurons he is investigating. The engineer, on the other hand,, cares that the model perform well on the task he has in mind. The two criteria can pretentiously work in cooperation to achieve the goal of understanding faster.

JAMES P. SHORES
NAVAL UNDERWATER SYSTEMS CENTER

The discussions were highly informative in many respects, particularly in the areas involving modeling of physical systems such as the ear. Future sonar systems will involve a very large amount of data channels from the sensor array, on the order of 104. It is clear that new ways of processing these channels are required. The model described by R. Lyon offers an attractive possibility. Secondly, neurophysiological studies are essential to provide the eventual inputs to AI systems which will provide the control part of the systems.

On a personal level, I found the exposure to new disciplines very rewarding, and hope that these activities will continue in the future.

NOBUO SUGA
WASHINGTON UNIVERSITY, ST. LOUIS, MO

Neurophysiological data obtained from the mustached bat indicates that the biosonar system has evolved in a goal-oriented way. The vocalization system produces complex acoustic signals suited for the species' biosonar. The auditory system processes biosonar signals in the parallel-hierarchical way to extract different types of biosonar information and eventually represents them systematically in the separate areas of the auditory cortex in the cerebrum. As examples, we discussed the neural mechanisms for processing of target distance and velocity information, because these two types of information are extracted by combination-sensitive neurons which are tuned to particular combinations of signal elements in the complex biosonar signals.

The neural mechanism found in the bat's auditory system may be shared by many different species of animals, including humans. During the present meeting, I have enjoyed discussions with the engineers, in particular, scientists working on speech processing. Their cross- or auto-correlation models are basically the same as a certain group of neurons which have been described as IBP filters. In other words, a group of neurons tuned to a particular parameter acts as the correlator. Words used by neurophysiologists are frequently different from those used by engineers. Therefore, at the beginning, we had thought that we were talking about different mechanisms for signal processing. This turned out to be not the case. There are similarities between neurophysiological data and the models, as well as differences. Further interaction between different types of scientists is obviously needed to reach the goal addressed in this workshop. Anyway, this workshop gave me a valuable opportunity to interact with engineers, in particular, speech scientists.

The neurophysiological studies on the bat biosonar system have explored several interesting mechanisms which have not yet been considered by electrical engineers. The human brain is unique and is specialized for speech production and processing. To understand the "acoustically" specialized human brain, the research on "acoustically" specialized animals is absolutely necessary, because such research has explored and will explore the neural mechanisms which have reached the upper limit of the auditory function in a particular domain. We working on the bat biosonar system have demonstrated and will demonstrate unique aspects of auditory mechanisms. Our research on the bat will thus be interesting and valuable for engineers, in particular, sonar and radar engineers and speech scientists.

TOM C. T. YIN
UNIVERSITY OF WISCONSIN

GENERAL COMMENTS

I feel strongly that an important enterprise for those of us working in neurophysiology, as well as in AI, is the development of models based, as much as possible, upon physiological parameters. Neurophysiological work is, or at least can be, sufficiently quantitative to derive such models. In addition, to make these models worthwhile to the other group, it is very important to facilitate the lines of communication between the two groups. This meeting is one of the few that has explicitly tried to do this, and for just this reason alone, it has been a worthwhile venture. These models should then be used by both groups to test explicit hypotheses, preferably to try to disprove one or more aspects of the model. The mammalian oculomotor system is a good example of the progress that can be made when models and physiology are used in close interaction. Only in this way can real progress be made, both in understanding neuronal mechanisms and in simulating natural systems with AI.

SPECIAL SUGGESTIONS

More specifically, for those working in the area of audition, I think an important finding is that, at least in the binaural system, there is now convincing evidence from many divergent sources (physiological, psychoacoustic) that a computation very similar to cross-correlation is needed for comparison of the inputs to the two ears. I believe that this correlation analysis is used for comparisons of both interaural time and intensity. This may also be used in the monaural channels as well, though there is much less evidence here. I believe that this correlation analysis may prove to be a general principle of neuronal processing in other systems as well. That is, a coincidence-like operation may be important for comparisons of other parameters. In any case, this gives a unique opportunity for interacting modeling and physiology with specific hypothesis, as described above.

Finally, I believe that AI systems, if they wish to model the brain, will have to take into account several important aspects that have been emphasized in neuroscience in recent years, namely, that the nervous system is highly plastic (self-organized), that it uses both parallel and serial processing, and that it has both feature detection and distributed parameters.

INDIVIDUAL STATEMENTS BY COGNITIVE PROCESSES WORKING GROUP

LOUIS HERMAN
UNIVERSITY OF HAWAII

The "cognitive revolution" has successfully involved many areas of biology, psychology, and computer science. Its influences have led to the development of a new area and a new focus on animal cognition. We are now approaching animals as if they were intelligent systems. The implications of this approach are profound and feed into the understanding of biological intelligence, supporting structures of the brain, and models of intelligent systems in AI applications and elsewhere.

I think I can best state how these thoughts apply to the results of this conference by posing a series of questions about the directions and implications for further research into animal cognition, particularly sea mammals.

1. What are the capabilities, specializations, and limitations in cognition of sea mammals, absolutely and relative to other mammalian taxa?

2. What do these described cognitive characteristics tell us about underlying cognitive processes or structures?

3. What theories and models of cognition can we derive from these analyses of cognitive processes and cognitive characteristics of sea mammals?

4. Can we develop systems and techniques to communicate with sea mammals in a more flexible, adaptive way?

5. Can we, through the development of such communication systems, interrogate sea mammals to learn more about their perception of their world, how they conceptualize and organize information, the type and complexities of representations used, and perhaps their ability to display self awareness and the awareness of others?

6. What kinds of intelligent processing takes place on received input to allow for categorical perception, generalization, abstraction, constancies, etc.

7. Can AI help us by modeling some of these processes, and can we help AI through the description of intelligent biological systems?

JOHN JOSEPHSON
OHIO STATE UNIVERSITY

A very stimulating workshop. There were many good discussions of hard issues in cognitive science; it was quite interesting to hear about recent advances in neuroscience. For interdisciplinary cross-fertilization, the workshop was a success. It would have been useful, however, to have had a few more AI researchers present. I'm afraid that most of the participants had little opportunity to learn about AI.

Studies of living systems seem to have a lot to offer to AI in the perceptual domain, where it appears that artificial systems will have to mimic structurally the biological ones rather closely. It is much less clear whether cognitive studies of humans or animals have anything to say to AI, or whether, in the near term at least, the significantly new ideas will primarily flow the other way. I should point out that AI is in an infantile stage as a science, and is explosively developing new ideas and theories and ways of looking at things. Which ones will prove to be significant for understanding natural systems, or for building artificial ones, will not be known for some time.

Despite the views of Karl Pribram and others, I remain unpersuaded that neuroanatomy has much to say about cognition. It still seems very likely that there are many levels of organization intermediate between the neural and the higher cognitive levels, each with its own form of organization and with its own set of appropriate abstractions. If we estimate that each level succeeds in organizing 10 component modules of the next lower level and estimate as 1016 the number of processing sites in the human brain (suggested by Bruce Halpern of Cornell), that leads to an estimate of 16 as the number of levels of organization. It is a long way from the neuronal to the higher cognitive levels.

J. C. R. LICKLIDER
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

GENERAL REACTION

Very stimulating to get an up-to-date look at fields (e.g., neurophysiology, cognitive psychology, comparative psychology) in which I was once actively interested. Some of the recent ideas and findings make me want to get directly involved again in the effort to understand how the brain works. It seems possible that great progress will soon be made on understanding the brain, progress comparable to that made during the last two decades in understanding the genetic process.

SPECIFIC IDEAS OF GREATEST INTEREST

- The voltage-sensitive dies that make the electrical activity of neural tissue directly visible. I want to find out all about them.
- Formalization and computer modeling of language experiments with aquatic mammals. I think that there is a great opportunity here for productive interaction between comparative psychologists/ physiologists and computer-modeling/AI people.
- Exploration of applications of low-level language-based electronic systems, applications too complex for single seromechanisms but not requiring AI treatment at the level of expert systems.
- Exploration of possible neutral analogs of "levels of abstraction," "layering," procedural abstraction", "data abstraction," "message-passing semantics," and related concepts of computer science. These concepts, dealing with the strategy of modular design, are surely pertinent to understanding the architecture of the nervous system.
- Understanding the brain as an information processing machine. Estimating the size and complexity of the brain in terms analogous to those used in measuring the "power" of a digital computer or the bandwidth of a communication channel. Surprised that there has been so little progress in this area--except in the realm of simple organisms, where the work has been quite exacting.

GENERAL REACTION, AGAIN

The process of establishing effective communication among representatives of diverse fields of research is not easy or short. This conference went a considerable distance in that process. That may be more important than any specific results achieved.

THOMAS MILBURN
OHIO STATE UNIVERSITY

I have found the workshop very worthwhile, primarily because of it as a way to getting acquainted with the state-of-the-art and the nature of trends in a set of areas that ordinarily look very separate from one another. I found many fascinating ideas, particularly ones from the sensory processes group. To get updated on dolphin research and comparative and some neurophysiological aspects of cognitive process research as occurred in the cognitive process group was particularly interesting. I especially benefitted from my interaction with J.C.R. Licklider, J. Josephson, and K. Pribram and feel that they benefitted intellectually from their interactions with one another. I now feel much more comfortable with AI and with the other areas here where I feel I have gotten pleasantly updated.

I enjoyed the group processes and my personal interactions with nearly everyone. I saw my role as facilitator, synthesizer, and summarizer.

H. KEITH NISHIHARA
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

The workshop for me was overall very rewarding and I think that its cost will be recovered many times over in the ideas that have been stimulated by bringing together this diverse group of people. Perhaps the best topic for a short reflection is my view of how the three fields: psychology, physiology, and artificial intelligence relate. It is natural for a member of any of these professions to believe that his is the driving methodology which will lead to a real understanding of biological systems. But I think that the most rapid progress toward understanding biology as well as producing effective artificial perception systems requires a close cooperation among all three areas. I see:

Psychology: Providing the best handle on defining what is possible in a perception system and providing guidance on the question of how the general problem of obtaining information about the world, can be modularized into separate perceptual modalities (e.g., in the case of vision into binocular stereo, structure from motion, shape from shading, etc.).

Physiology: Gives us clues about the fine details of how things are being done in a working system.

Artificial Intelligence, or more precisely computational studies, help us to understand better the nature of the abstract problem to be solved (once it is defined). Why is it hard, what are the principal issues that have to be addressed in order to make a workable solution, what algorithmic choices are there?

Each of these activities/endeavors contributes important guidance to the others and uncovers new questions that often are more easily answered by one of the other areas.

KARL PRIBRAM
STANFORD UNIVERSITY

This has been an extremely useful meeting for me in clarifying several issues, reviewing and updating my knowledge base, meeting and interacting with old and newly acquired friends. Some of the specific topics which were discussed during sessions and after:

1. with Ted Bullock: the use of evoked potential techniques (especially in the teasing out of parallel processes) as a tool for comparative physiology; the use of horizontal rows of multiple mircrolectrodes (similar to Petche's vertical rows in Vienna) to study neural patterns.

2. with Nobuo Suga: the multiple selectivity of cortical neurons; methods for decoding which selectivity was paramount (arrangement and sharpness of turning curves); whether the output of cortical cells is coded as a temporal pattern which is feature-specific or whether coding is based on spatial patterning; the role of the prestriate cortex of monkeys in constancy (size, color and object) and the similarity of patches in that cortex to patches in bat cortex which code echolocation; the recent work on the functions of inner and outer haircells (broad and narrow tuning) of the cochlea and the effect of the olivocoelilear bundles (crossed in outer haircell function.

3. with Stephanie Seneff: the differences between autocorrelation and cross correlation functions in modeling auditory function (with special reference to delay lines, differences between frequency and pitch codes etc).

4. with Marvin Minsky: whether animal behavior studies indicate that they are capable of "reasoning."

5. with Lou Herman and Ron Schusterman: similarities and the differences between language-like "reasoning" processing and the nature of a brain model which allows for recombination to take place.

6. with J. C. R. Licklider and John Josephson: the difference between a feedback-based and a feedforward-based model of cognitive processing. The details of what a model of complex feedforward representation would look like remains one of the most important (for me) unfinished theses on the agenda.

7. with Michael Arbib: the difference between an emergence and a transcendental model of the brain/mind relationship; the modeling of cooperative computation in motor systems.

8. with Bill Uttal: whether it is all worthwhile, especially whether microelectrode brain studies can tell us anything about psychological processes. While Uttal remained pessimistic and I, on the basis of achievements already attained, was optimistic, we both agreed that the brain/mind relationship must be approached by seriously attending the various levels involved: molecular, neural systems, sensory motor, cognitive, etc.

9. with Bob Glaser: the importance for education specific knowledge bases and language systems which give several views of the same knowledge base.

10. with Don Woodward and Ron Schusterman: whether syntactic rules are "learned" and used to manage cognitive processes, or whether they are a by-product of innate generative mechanisms. The issue is whether one should search for rules or generators. As a practical matter it may be that one can infer what the generator must look like only from knowledge of the system of rules which are observed to operate. This is a second important unresolved issue on the agenda.

11. with Mike Merzenich: the difference between automatic and controlled processing and the modifiablility of the neural substrate even in the primary sensory (e.g., visual, somatosensory) systems; details of somatosensory representations; frequency encoding in the somatosensory systems.

12. with everyone: the similarities and differences between auditory, visual and somatosensory processing; cross modal processing; the importance of motor systems in the production of object constancy; comparison of frequency domain and statistical descriptions of central processing.

RONALD SCHUSTERMAN
CALIFORNIA STATE UNIVERSITY, HAYWARD

I think it is correct to be critical of those aspects of cognitive psychology which suggest that unverifiable factors control behavior (e.g., "insight" or "gestalt") either endogenously or exogenously. Behavior that is "insightful" or "creative" or conforms to "gestalt" organizing principles may best be described as resulting from the integration of several acquired or innately given action patterns. I should point out that, although this conference was divided into subgroups (cognitive, sensory, mechanical and neurophysiological), cognitive functioning is not independent of sensory and motor functioning. To talk of a mere structural arrangement without considering how these things form a unitary whole in their interaction with each other and the way in which the whole organism does commerce with the environment is an expression of Cartesian dualism.

I suggest that the ability to solve complex problems, even those involving symbolization and sematic comprehension depend to a large extent on "interconnectedness" of distinct behavioral repertories (whether acquired or innate or some combination of the two). Many different species share the underlying abilities to solve complex problems "creatively" and it is the job of the comparative psychologist to discover the factors (both environmental and organismic) influencing the appearance of novel or "creative" problem solving behavior.

I would caution cognitive scientists to distinguish carefully between descriptions and interpretations of their data. Further, I caution them not to abandon the law of parsimony in favor of using intangible evidence attributing to nonverbal animals the highest intellectual abilities. Rather, conforming to the law of parsimony while seeking the limits of animal cognition should be their avowed goal. It is my hope that as comparative psychologists working on animal cognition interact with AI workers they will develop measurement and computing devices which will enable them to reduce the use of concepts like "insight," "creative," and "understand," etc. in favor of more behavioristic terminology.

Finally, it should be noted that dolphins and sea lions can be trained or "programmed" to carry out actions on specific objects where the commands are made up of separate signals which can be recombined in different ways and therefore can convey different meanings (the characteristic of semanticity). It should be possible to develop a "program" to mimic the behavior of dolphins and sea lions. Such a program should prove extremely useful if it is just as capable of accounting for characteristic errors as it is for correct behavior.

TIM WADSWORTH
NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CALIFORNIA

Previous to this workshop, I was unaware of the impressive artificial language work being done with dolphins and sea lions. The description of the experimental designs and results were fascinating and will provide for some interesting contemplation on the mechanisms of concept formation and symbolic communication.

I have long been interested in neurophysiology and was very pleased and excited to see that Karl Pribram would be in our group. I was also grateful for the reprint summarizing much of his recent work, as I have been out of touch with this field for the past ten years and have wondered what was going on.

I came to this workshop as a representative of the AI community, but, as a matter of fact, I have, at this point, a much stronger background in the cognitive sciences and was much more interested in and impressed by the information presented from that orientation.

DONALD P. WOODWARD
OFFICE OF NAVAL RESEARCH

GENERAL COMMENTS

1. The positive assumption that each field (area) has something to contribute to the others; relationship should be reciprocal, interactive. The problem(s) is (are) large but the assumption must be made that they are solvable eventually. No specific time limit should be set, but there must be a means for recognizing when one gets locked into an endless loop.

2. There are levels of organization: research on each level is appropriate and does not need special justification. No one level is necessarily more important than another. It may be possible to move up or down levels to find enlightenment on other levels. The action should incorporate both "Top Down" and "Bottom Up" approaches so that there is some forming of compatibility between levels.

3. The goals of each area should be made explicit — if they are different, how they differ. One might ask if they should be/could be made the same. There is probably some common methodological approach among the areas but I don't know what it is.

4. The study of simpler biological systems is probably necessary but is unlikely to be sufficient for explanation of increasingly complex systems. I wonder the extent to which the simple systems might be integrated to form larger complex systems; what gets changed or modified, do simple systems lose their identity; how and where is the plasticity of the nervous system demonstrated, i.e., at the ionic, membrane, cellular, system level; how is the plasticity at any one level altered/modulated by "higher" levels.

5. Overall, I would rate the meeting as successful. I feel I worked some, learned some, and generally enjoyed myself. Many thanks for all the hard work.

INDIVIDUAL STATEMENTS BY BIOMECHANICS WORKING GROUP

EVAN C. EVANS III
NAVAL OCEAN SYSTEMS CENTER, HAWAII LABORATORY

As Marvin Minsky said in his introductory address: our language equips us poorly to discuss intelligence. Similarly, our present understanding of the molecular biology of muscle action equips us poorly to design a practical device that emulates that action. Nevertheless it is quite apparent from the deliberations of this working group that we now know enough about muscle operation to begin such an attempt. We cannot expect successful emulation on the first few tries, but each successive attempt will move us closer to our ultimate goal.

The basic problem is one of mechanochemistry and control. The "walking" of one filament (myosin) upon another (actin) appears to be a nearly universal process in nature. This statement is particularly reinforced by Sheetz & Spudich's demonstration of an animal component operating on a plant component, rabbit HMM "walks" on Nitella actin (Nature 303, 3135 (5 May 1983)). This mechanism avoids inertial losses while at the same time provides both fine control and static rigidity with minimal consumption of energy. The biological actuator is unlike any of the force-generating mechanisms currently employed by engineers. Precisely this fact greatly stimulated our discussions. We were collectively striving to devise something truly new.

As a group, we had broad quantitative knowledge of:

- engineering materials and structures,
- sensing and teleoperations equipment,
- control and feedback technology,
- interactions with the environment (stability, navigation, active and passive boundary layer conditions)
- basic mechanisms (and limitations) of muscular action,
- various natural methods of motion and locomotion,
- simulation of biological movement by engineered devices.

After careful discussion, the group identified the fundamental problem of first selecting a suitable material and then working out the mechano-chemistry of that material so that controlled force generation was possible on a sustained and repeatable basis. Control and energy source problems were recognized, but it was felt that these problems would largely be solved by advancing technology. The group agreed that whatever the actuator developed, its ultimate evaluation must stem from an application in one or more systems that accomplished a specific task. The interaction of AI with the group's endeavors would come principally through computer-generated models for the design and testing of such application systems, and through the development of sophisticated control systems for their operations.

(See also BioMechanics Working Group Summary, prepared and presented by Evans.)

AMOS FREEDY
PERCEPTRONICS

HIGH PERFORMANCE DISTRIBUTED ACTUATOR SYSTEM

OVERVIEW

The following memorandum summarizes my technical ideas and views which are relevant to the development of high performance artificial muscles with rich sensory control for achieving mechanical compliance and functional versatility to achieve increased end-effector accuracy and variable rigidity. A major element in constructing such capabilities is the development of a distributed actuation and sensory system, using living systems as a model. A major element of our approach is the employment of new typed of active distributed actuators, artificial muscles, tendon-type actuators and goal directed sensor control software.

TECHNICAL VIEWPOINT

One of the most consistent observations that can be made about living systems is their hierarchical structure-function relationships from the molecular level to the macro behavioral level. Within each level there is a complete and orderly set of interrelationships that consist of energy exchanges and command and control processes. When aggregated, the processes intersect and interact from one subsystem to another, providing the transitions necessary to form behavior that transcends the qualities of the parts and produces new qualities that are often unexpected and always more complex than the subsets.

Taking such observations as a model for man-made contructions, there are implications that currently designed man-made structures have only just begun to spread downwards into the more micro levels of functional relationships. For example, the tendency in mechanical design has been to work with relatively straightforward, often quite massive, prime movers that apply forces from a central source through a drive train to a remote effector. The level is analogous to the use of bones as levers pulled by the gross output of muscle masses. What is left out of such a simple model is the distribution of microsensors and the accumulated effects of tightly controlled micromotor events that make up what seems to be a gross movement. The importance of these microevents is demonstrated by the control of the gross motions that an athelete can achieve through systematic training and practice. It is these distributed microsensory-micromotor control loops that make the variable compliance of limb and body movements possible. It is the flexibility and adaptability of the accumulated microunits of function that can fine tune more rigid structures, e.g. bone and joint support, to provide the skilled actions of a surgeon or a musician. Without these peripheral capabilities, no amount of cognitive action could interface effectively with the problems of the physical world.

For applications to robotics and teleoperators and the need to examine the possibilities of distributed microsensory-motor systems as a serious approach toward obtaining increased efficiency and versatility is almost self-evident. Based on the success of the universal application of such an approach in living systems the probability of success for man-made devices

carried minimal risk. However, a great deal of research and development is ahead before such devices can be brought to fruition.

DESIGN APPROACHES

One potential design scheme would mimic microscopic structure of actual muscles. Force in the muscle is developed at the level of the motor unit. Each motor unit consists of several muscles fibers (contractile elements), their actuating nerve (control element), and various feedback units. To produce a small, discrete, finely controlled contraction only a few motor units are activated. As the force of contraction increases more motor units are called into play in a tree-like pattern. A system of microactuators could be designed along exactly the same principles.

To go in this direction, three approaches to microactuator units are proposed for investigation and prototype development. The first approach is the use of miniature serpentuators. There are tentacle-like devices made up of a series of flexible interlocking spools as the core with threadlike strands in paralled distributed longitudinally around the periphery. Selective contraction of the strands to displace the force balance produces a controllable torque at the tip of the unit. Such units could be strung together in series or paralled to provide various combinations and directions of force outputs.

The second approach is to construct a mesh of fine wires or fibers surrounding globules of rubber-like or plastic material that is impregnated with micro particles of a magnetically sensitive substance. Tiny independent electrically conductive loops distributed among the mesh of globules could be systematically activated to produce selected patterns of contraction in the mesh.

The third approach is to align a series of overlapping disks, each disk a powerful magnet with one half as a north pole and the other half as a south pole. Each disk would be mounted on an axle, the other end of which was in a slot. When the axles were systematically rotated the series of disks would attract or repel each other producing a shortening or lengthening of the series. Increasing the number of disks on each axle would provide a means to accumulate the total force output that was available. Additionally, the use of interlocking cylinders could provide direct torsional force output.

DOUGLAS W. GAGE
NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CALIFORNIA

Biological systems provide many useful models for robotic system builders in, among other areas, materials, structure, and control paradigms. Knowledge of all but the most obvious of these models is not, however, generally easily accessible to most robotics researchers. Biologists must be made aware that robot developers represent an emerging client community, and it may at some stage make sense to direct some biological research to areas most useful in robotics (analogous to the expansion of solid state physics to support the development of electronic devices).

Interdisciplinary workshops like this one represent a highly cost effective first step. Future such workshops should address specific target areas such as artificial "muscles" or closed loop manipulator control. The decision to apply resources to achieve biological "technology transfer" in a particular functional area (e.g., to develop an artificial muscle) should be based on a number of criteria such as:

1. How well do we know how nature does it?

2. How hard would it be (in terms of time, resources, and risk) to find out more about how nature does it?

3. What would be the payoff if we could do it the way nature does it (considering, for example, what alternatives exist to achieve the same function).

4. How hard would it be (in terms of time, resources, and risk) to develop the means to do it the way nature does it?

In terms of these criteria, it would make sense to investigate the development of artificial muscles as a medium range goal. It would clearly not make sense to consider the development of an artificial brain as anything but the longest range goals.

J. D. HIGHTOWER
NAVAL OCEAN SYSTEMS CENTER, HAWAII LABORATORY

This workshop provided a very productive forum for several investigators working in different but related disciplines to interact together in formulating priorities and philosophical approachs for R&D programs in biomechanics/AI. Major objectives of developing bio-like actuations with distributed control and AI tools for modeling were developed. In order to realize the objectives, I believe it will be necessary to estabish and sustain high level continuous support for perhaps a decade or more. I believe it was felt by most, if not all present, that a bionic institute or center would be the most efficient way to pursue development of this technology area. If nothing else, such a "center" could be a collection of a relatively few individuals co-located at an existing facility for coordination, planning and monitoring progress but possessed of appropriate authority and responsibility.

FLOYD HOLLISTER
TEXAS INSTRUMENTS

ROLE OF AI IN CONTROLLING SYNTHETIC MUSCLES ARRANGED INTO BIOLOGIC-LIKE STRUCTURES

Our presumption is that large numbers of synthetic muscles could be formed into complex structures that might mimic biologic structures and allow natural movements. Thus, structures such as fingers, hand, wrist, forearm, elbow, upper arm, shoulder, etc. might be constructed. We also presume that biologic-like motions such as grabbing, turning, pushing, etc. could be performed by these structures under computer control. An assertion is that Artificial Intelligence can play a role in such control. The question is what does AI have to offer. The balance of this section attempts to partially answer this question.

An objective of the AI community is to manage complexity by providing tools that support programming at increasingly higher levels of abstraction. AI languages, such as USP and SCHEME, support abstraction. They do this, in part, by allowing problem-specific languages to be written at increasingly higher levels of abstraction. Thus, the programmer is able to focus his or her attention on the problem-relevant aspects of programming rather than on the language-relevant aspects.

One example of this ability to abstract is found in object-oriented languages such as Smalltalk. Such languages allow programmers to focus on the specific entities of which a problem is comprised and their interrelationships. In our context of synthetic muscles and limbs, objects might be specific muscles, fingers, wrist, etc. A feature for communications that some object-oriented languages support is message-passing. Message-passing allows objects to exchange messages with other objects. Such messages can convey data or procedures. This exceedingly rich communications media seems well suited to control of synthetic muscles, and hence the structures that they power.

The ability to pass procedures as well as data among objects can be used to implement different strategies of muscle control, depending upon the nature of the motion, the environment in which control to be performed, and the degree of control desired.

The AI concept of scripts as a means of knowledge representation may be very useful in mimicking animal-like motions in different environments. There might be such scripts as the "walking across flat terrain," "climbing over obstacles," "walking softly over boggy ground," etc. Scripts can also be useful in making intelligent inferences, perhaps about those features of the environment that cannot be sensed. Knowing which script is operative and being able to sense some elements of the environment allow knowledge about the environment to be inferred from the script.

AI-based planning systems may also be useful in planning the motions of the limbs (or other elements) of robotic structures in performing grasping, lifting, balancing and similar motions.

The powerful graphics capabilities of modern symbolic processing could be used in conjunction with object-oriented computing to develop realistic and easily modified functional simulations of biologic structures. Such functional prototying could allow many designs to be rapidly simulated and evaluated at relatively low cost prior to their physical construction in hardware.

In the near term, the greatest contribution of AI in muscle-control is likely to come from AI tools and problem-solving techniques, as described above.

In the mid-term, AI is likely to make its greatest contribution in implementing higher levels of control (such as limb coordination) in the presence of environmental uncertainty.

In the far-term, AI is likely to contribute most in the areas of image understanding and learning from experience.

ROBERT MCGHEE
OHIO STATE UNIVERSITY

My research interests center around mobile systems capable of physical interaction with their environment and demonstrating as much autonomy as possible. My research to date has been concentrated on the problem of land locomotion as it relates to such systems, especially with respect to vehicles exhibiting omnidirectional motion and possessing abilities to overcome large obstacles and other adverse terrain features. Briefly stated, the class of machines I would like to see realized would have mobility characteristics more akin to those of large cursorial mammals than those of conventional off-road vehicles. In the DARPA Autonomous Land Vehicle program, such machines are referred to as adaptive suspension vehicles reflecting the belief that improved mobility requires active control of the relationship between a vehicle and its supporting elements, no matter whether such elements are wheels, tracks, or non-rotating pads. The latter case constitutes a special subclass of adaptive suspension vehicles commonly referred to as walking machines. My own personal research relating to adaptive suspension vehicles has been limited to walking machines.

Serious work on walking machines with a potential for military application began at General Electric Corporation about twenty years ago with the support of DARPA. At that time it was felt that the most difficult problem for such machines was that of limb motion coordination. This problem was solved by GE by incorporating a human operator within a quadruped vehicle and controlling joint motions and torques by means of master/slave manipulator technology in which each limb of the operator controlled one limb of the vehicle. This approach was marginally successful, but was judged impractical after field tests in about 1970.

The partial success of the GE machine inspired research aimed at the realization of walking machine autopilots capable of elevating the human control problem to that of body motion control with leg motion coordination being accomplished automatically. This problem has been solved to varying degrees in several research centers in the United States, the Soviet Union, and Japan. In particular, a new vehicle nearing completion at Ohio State University, called the ASV-84, will feature aircraft-style controls and an optical terrain scanner capable of providing a terrain elevation map in real time to permit automatic foothold selection and body terrain-following under the control of an on-board computer.

The mechanical design of the ASV-84 was strongly influenced by biomechanical studies of animal locomotion. While component tests to date support the belief that animal-like mobility will indeed be attained by this machine, and that the on-board autopilot will reduce the difficulty of the control task to roughly that of flying a light aircraft, two major problems remain:

1. It would be highly desirable to remove the operator from the vehicle in order to increase its operational potential, especially for military or other hazardous duty applications.

2. The energy efficiencies achieved to date in component testing indicate that the fuel economy of this vehicle will be roughly the same as that of

tracked vehicles of similar size and speed. In contrast, animal energy requirements for locomotion over the same type of terrain are at least an order of magnitude lower.

The solution of the first of these problems requires advances in both programming methodologies (AI) and in computer hardware (imbedded computers for symbolic processing). The AI problems include both perception of terrain features relevant to locomotion from (ranging) vision, and route planning and foothold selection. The solution of the second requires the development of actuators capable of conversion of chemical or electrical energy into mechanical energy with high efficiency. However, unlike most currently available efficient motors, the desired actuators must develop very large forces with small motion, much like the action of natural muscle.

In summary, I believe that it will be possible to create mobile systems with behavioral characteristics close to those of large mammals within the next twenty years or so. The two major problems standing in the way of realization of such systems are those described above. It is my personal view that the AI problem will be easier to solve than the actuator problem.

H. E. VON GIERKE
AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY

The creation of systems to perform functions traditionally performed by human operators or to exhibit specific characteristics observed in living systems starts with the analysis of the desired biological capability followed by the partial copying of this capability in the engineering design. This approach cannot be better than an understanding and quantitative description of the biological processes to be emulated. This applies to the whole spectrum of properties from materials, structures, receptors, information processing to decision making, output effectors and control. Therefore, a strong theoretical biomathematical effort analyzing and modeling the system according to present capability must lead and accompany such efforts and must be a capability specifically and separately fostered. In the development of "intelligent" biomechanical or any other intelligent system this capability should lead and unite the various disciplines of necessity involved in such an undertaking. Unfortunately this is frequently not the case and broad-based theoretical works and modeling in biosystems is not widely supported. Theoretical biology is not leading biological experimentation to the degree theoretical physics interplays with experimental physics. When in the early 1960s the term bionics evolved it was conceived as the unifying bridge between the life and engineering sciences leading to mutual cross- fertilization and collaboration. The mathematical-analytical disciplines and/or model was seen as the unifying common language. Theoretical studies in biological pattern recognition, decision making, learning, control and other theoretical areas were seen as the cornerstone of the bridge.*

Overoptimistic expectations and short term funding policies resulted in discontinuation of this approach after barely a decade of extremely productive existence with minimal funding. Although some hardware payoffs from these efforts are still surfacing now more than 10 years after termination of the first bionics program, it is deplorable to notice at this conference that other areas made, in the interim, little or no progress.

What are the lessons to be learned for future endevors in this area of bionics, biocybernetics, robotics or artificial intelligence? Most biological systems or capabilities worth copying are so complex that an understanding of them will remain incomplete for some time to come and we can hope only for slow gradual progress. Our hope must be in truly multidisciplinary collaboration with the various sciences represented as equal partners on the team. Interdisciplinary symposia such as the present one common data bases and electronic communication are all helpful but cannot replace the day to day team interaction. This applies particularly to theoretical biology and modeling if it is to be truly interactive with experimental biology as well as with creative hardware conception and AI. Based on these thoughts and following up the present symposium, I have these recommendations:

1. Foster and support primarily truly interdisciplinary teams in academia, government and industry. Support broader interdisciplinary research

*See "Principles and Practice of Bionics," Von Gierke, Keidel, Oestreicher, editors, AGARD Conference Proceedings No. 44, 1970 (Library of Congress Catalog Card No. 70-82417)

goals over a 3 to 5 year time period with multidisciplinary peer review by groups such as the present one.

2. Strengthen biomathematics and quantitative modeling in each subarea such as receptors, information processing, pattern recognition, decision making, biomechanics etc., but encourage it as part of larger team effort.

3. Select demonstration areas for hardware demonstration of bionics principles and for interaction of biological, mathematical and AI science. (Examples discussed by the biomechanics group; walking machine, swimming machine, manipulator. Exoskeletons deserve further discussion.)

4. Reconvene the present symposium group and concentrate discussion on a few specific capabilities or demonstration projects/proposals. Prepare for the symposium by having detailed technical summary papers (but not too specialized) as introduction and basis for discussion or critique. These will have to be prepared by consultants or study contracts and should analyze the specific problem from the different viewpoints, solicit comments and suggestions for future studies.

JAMES F. WILSON
DUKE UNIVERSITY

Professor Marvin Minsky of MIT gave the keynote address. He talked about intelligence, the human brain, and problem solving. These thoughts, which generated some lively discussions, are elaborated upon in his forthcoming book.

The Biomechanics working group began with a general description by J. D. Hightower of the U.S. Navy's need to develop remote handling machines for hazardous areas. Desirable characteristics of such machines include adaptability, control of "artificial muscles" acting as actuators, and some degree of artificial intelligence such as the ability to learn while adapting. Artificial muscles need to be developed for actuators that are mechanically efficient and fast-acting, with high strength-to-weight ratios.

After each group member briefly discussed his area of expertise, three presentations on biomechanics were made to this working group. First, Robert McGhee reviewed his current research and development of walking machines, the problems of mechanical design and control, and pratical limits of walking without flight. Second, James F. Wilson discussed the muscle structure of selected lower animals and presented his research on modeling the geometry, the motion, and the manipulative ability of these animals using continuous actuators, or pressurized clusters of tubes that extend, bend, twist, and coil. Third, Evan C. Evans categorized Biomechanics into three components: Bioenergetics, Mechanics, and Biofunctions, where each involved both the interior (muscle action, materials, energy storage) and the exterior (environment, animal covering, overall motion). The interface of Biomechanics with the other working groups was depicted graphically.

The working groups then summarized their findings. The Neurophysiology and Artificial Intelligence teams pointed out the need to understand the living, human brain on the local and global functioning levels, if we hope to develop similar but artificial forms of perception. Those in the Sensors group spoke of training dolphins for retrieval, and of the need to understand the recognition processes for simple animals. This latter group recommended short term research in several areas, including parallel processing, movement detectors and sensors with interaction of tactile, vision, and motion.

In a second meeting of the Biomechanics working group, the question was posed: How can Artifical Intelligence interface with actuators? In addressing this question, Robert McGhee indicated the need for control which, in the context of walking machines, would start with classical control theory, progress to the coordination level, and then to the new frontier of a sensing machine that would make discrete decisions. Floyd H. Hollister indicated the availability of the programming language LISP (Jerry Sussman of MIT) that may aid in writing particular languages for control.

Unfortunately, I left a day early so I did not hear the final reports of the working groups. I shall read this final summary with interest.

The organizers of this workshop are to be congratulated for their hard work in making this a very successful enterprise.

THEODORE Y. WU
CALIFORNIA INSTITUTE OF TECHNOLOGY

The following comments and recommendations are offered on the basis of an individual member of the Biomechanics working group, with intent to supplement the Group Work Report.

GENERAL

The discipline of biomechanics related to bionics and bionical applications is a subject of increasing importance as one of our essential national resources. Its growth and advances require a continuous close collaboration between several principal disciplines that conjointly support and underlie the very foundation of this new multidisciplinary field; they include, at this stage, at least biology, mechanics, electrical engineering, material science, applied mathematics, computer science and artificial intelligence, and would embrace some other fields that will arise to join the interacting group along the course of future development. In order to foster highly rewarding advances of this subject, it is therefore essential to establish and maintain a central coordinating office, which can act as the headquarters to help various participating groups effectively collaborate, interact and exchange new ideas on focused problems of timely need and long-lasting value.

SOME CORE PROBLEMS

In order to help in fostering the development of "intelligent" biomechanical models and mobile systems that are capable of executing motions and movements which can be controlled by AI, it is of primary importance, I believe, that the fundamental biomechanical studies of animal locomotion be given continuous strong support so as to achieve, by accumulation, a rich archive of basic knowledge that can greatly facilitate desired applications. The required studies can be carried out from two comprehensive and mutually complementing approaches:

1. Various Scales of Biological Motions. From the standpoint of biological scales, motions and movements occurring in the biosphere can be classified into three levels:

molecular scale - dealing with protein molecules, muscle, etc.;

cellular scale - protozoa, intracellular motion;

organism scale - organ, organelle, and whole organism.

In the investigations of these problems, the biological and mechanical aspects of study can vary greatly from one to another level of scale. However, the fundamental knowledge acquired from studies for these different cases are all valuable for estimating and predicting energy requirement, power supply and distribution, modes and patterns of movements, biochemical and mechanical efficiencies, safety factors and redundancy, stability and reliability, etc. of the required motion.

At the macro-molecular level, new understanding is being attained from recent studies on the supply, propagation and expenditure of biochemical energy. Invariably, the primary source of the biochemical energy comes from the hydrolysis of the ATP molecules, generally considered as available and abundant in every biosystems. From this process, an energy of a unit of about 0.5 eV (electron-volt) is furnished and then propagated along an α-helical protein molecule in the form of a long wave (like a soliton). With this energy supply, vibration of a single-valence bond can be excited (to an energy level of about 20 times of the thermal energy of physiological temperatures). Whether this type of energy supply and distribution can be adopted as a desirable prototype to develop and simulate artificial engineering devices of course cannot be concluded without further concentrated studies.

2. Media and Environments. From this viewpoint, the motility of organisms can be classified into three groups.

i. aquatic animals - swimming, flagellar and ciliary locomotion.

ii. aerial animals - flying, soaring, dynamic soaring, hovering, wave skimming, etc.

iii. terrestrial animals - walking, running, jumping, crawling, burrowing, etc.

This classification is very useful because the fluid mechanics and applied mechanics involved in analyzing these animal motions depend on the media in which the motion takes place and on the size and geometry of the animal in question. The scale of mass of all these motile organisms spans over 19 orders in magnitude, ranging from bacteria (~ 40 μm long) to the blue whale (~ 30 m long). The (dimensionless) dynamic parameters that characterize these various classes of motions can have considerably different relative importance for different generic groups. Their major roles, when clearly understood, can provide valuable information and guidance for design and construction of artificial mobile and working systems and can further be used as relevant parameters for AI computation and control.

BIONIC TECHNOLOGY

Several specific mission-oriented projects have already been under investigation and development. They should be given support to continue in order to achieve the goal and objectives originally intended, with possibly additional technical support from active and interested workers in the related fields, as the interdisciplinary interaction is being now extended through the contacts initiated at this workshop.

In addition, the group is urged to endeavor, by group discussion and other means, to establish, to monitor, and to keep updating a Bionic Technology Program that identifies core problems, basic needs, and useful building blocks that can greatly facilitate the future development of intelligent mobile and working systems, with or without AI control.

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This workshop on Artificial Intelligence and Bionics has been a rewarding meeting from which I have learned a great deal. Discussions with other researchers in the various different fields have been mutually beneficial and have led the way for future communications and collaboration. Our working session on biomechanics has identified some areas for future research within its own boundaries and some guidelines for the development of artificial intelligence. Rather than repeat these group comments, I would like to express some general feelings and recommendations.

Biomechanics, by its very nature, is an interdisciplinary subject which must be approached with contributions from all the various fields of engineering, physics, applied mathematics and biology. It encompasses both internal and external fluid flows and analysis of various biological structural elements. Even if we confine our attention to the issue of movement in biological systems, the range of diverse fields is extensive. Contributions are needed in biomaterials (the constitutive properties of biological fluids, solids and soft tissues), bioenergetics (the storage, distribution and efficiency of energy conversion), analysis of the motion kinematics and an optimization of the parameters involved in generating and maintaining the motion. Communication between researchers in the various disciplines is a first and necessary step and may in part be aided by electronic mail service such as ARPANET. A fragmented approach is suboptimal and there is a real need for continuity and stability in any research effort which combines such diverse fields.

The basic understanding of the activation, performance, maneuverability and control of man-made vehicles or other devices can still benefit a great deal from a fuller understanding of biological systems. This is true for all the areas of biomechanics and AI, and is especially true in the case of aquatic animal swimming where new observations have recently indicated potential hydrodynamic benefits. Despite the large fluid forces acting on fish their specific energy cost of transport has been measured, and is the lowest of all animals. Besides possible drag reduction advantages, hydrodynamic investigations of high performance swimmers promises to enhance the control, stability and maneuverability of marine vehicles.

The most prominent point that I would like to emphasize is the importance of concentrating on the fundamental physical concepts exhibited by these various biological systems. By placing attention on the critical analysis of the underlying principles, the potential application to engineering problems of practical importance will follow most directly and with most general utility. To this end, whenever possible, simple model systems which clearly illustrate a point, should be isolated and selected for detailed investigation.

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